Pair-instability surpernovae explosions (PISNe)

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THESEUS WORKSHOP, NAPOLI, 5-6 October 2017

To take Home…

The process of ignition and propagation of burning plays an important role in determining the observational outcome of an explosion.

references

On the pair-instability supernovae and gamma-ray burst phenomenon
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Piecewise parabolic method on local stencil in cylindrical coordinates for fluid dynamics simulations M. V. Popov,
Comput. Mathem. Mathem. (2012) Phys 52, 1186

Multidimensional simulations of pair-instability supernovae
A.A. Baranov, P. Chardonnet, V. M. Chechetkin A. A. Filina, M. V. Popov
A&A (2013) 558, 10

Aspherical Nucleosynthesis in core-collapse supernovae
M. V. Popov, A. A. Filina, A.A. Baranov, P. Chardonnet, V. M. Chechetkin
ApJ (2014) 783, 43

Gamma-ray bursts appear simpler than expected?
P. Chardonnet, A. A. Filina, M. V. Popov, V. M. Chechetkin, A.A. Baranov
Astronomical & Astrophysical Transactions, Vol. 29, Issue 2, p. 109-128

Multidimensional simulations of pair-instability supernov

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ABSTRACT

According to theoretical models, massive stars with masses within the 100–250 $M_{\odot}$ range should explode as pair-instability su|
(PISNe). Since the first stars of the Universe are believed to be very massive, these supernovae should play a significant ro
early stages of its history. But these stars represent the last unobserved population, owing to detection limits of current tel
In this work we analyze pair-instability supernovae explosions using various numerical codes. We evolve series of the config
of oxygen cores to establish a range of masses and initial conditions where this type of explosion is possible. We also study
of possible instabilities in the propagation of shockwaves during the last stage of the explosion. This investigation could h
predict the observational properties of PISNe for future space and ground telescopes.

Key words. stars: Population III – supernovae: general – hydrodynamics – instabilities

1. Introduction

The first stars of the Universe, called Population III stars (Pop III), are rapidly becoming an important subject of investigation from the point of view of theory and observations. The formation of these stars hundreds of millions of years after the Big Bang marks the end of what is called the "Dark Age". Today's telescopes cannot look far enough into the cosmic past, so we do

or by collapse to a black hole. In the case of PI
ergy release is tremendous and could possibly be s
telescopes (*James Webb* Space Telescope, Europe
Large Telescope).

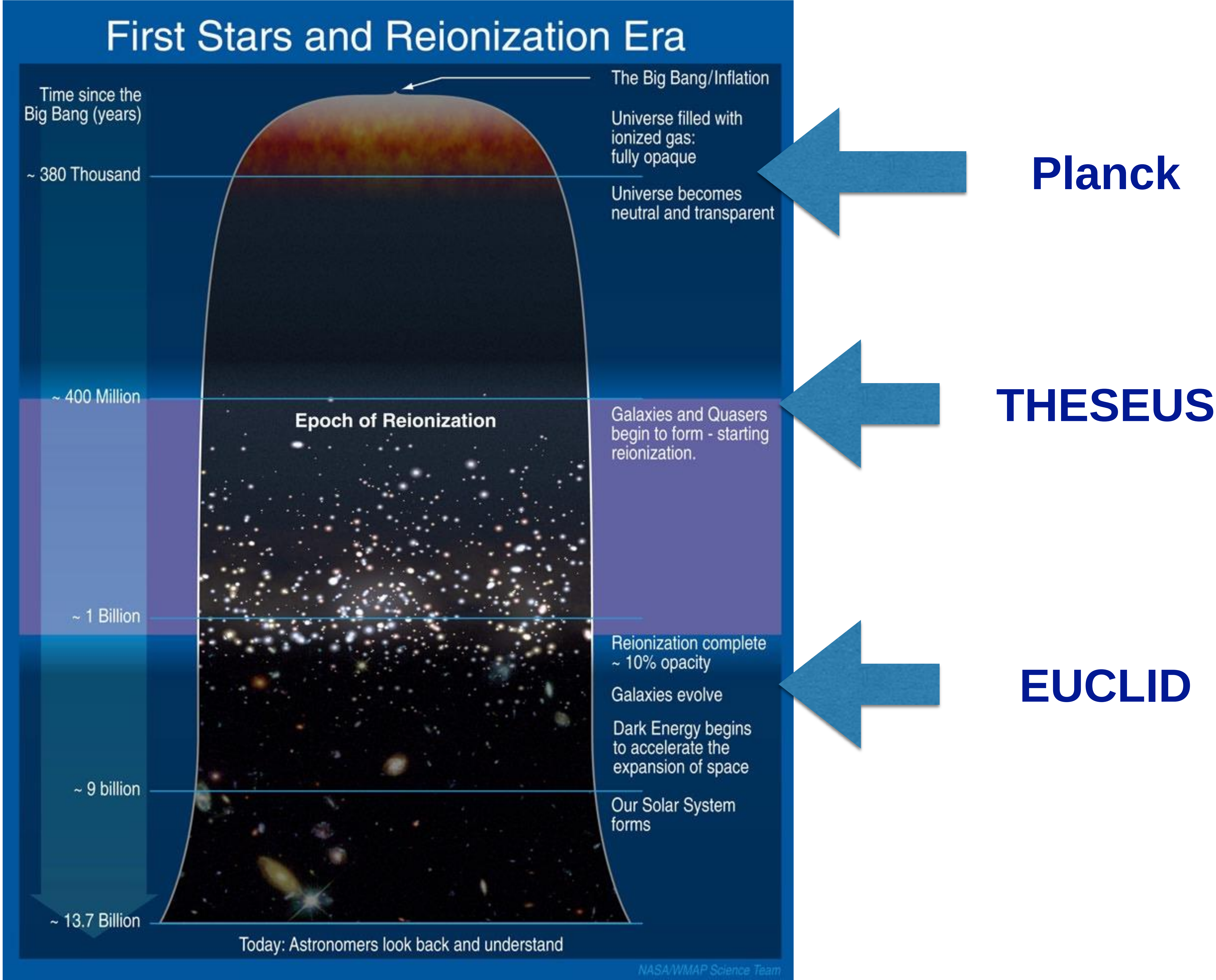
In this work we analyze the PISN explosic
present the results of one-dimensional simulatior
sis of the fate of a star depending on physical conc
recent articles (Chen et al. 2011; Joggerst et al. 2

Outlines

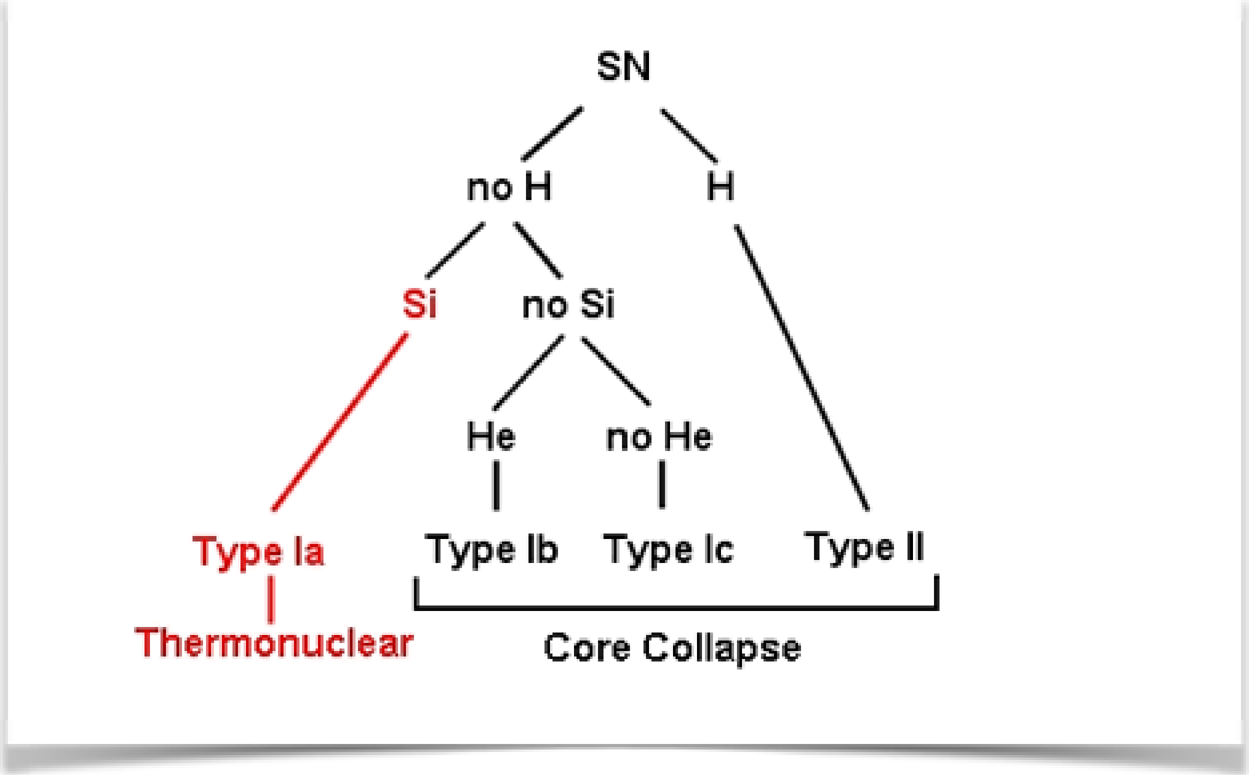
- Introduction
- Simulation setup
- Results
- Conclusion

Introduction

- Introduction: general context
- What is a pair instability supernovae explosion?
- Some results


First Stars and Reionization Era
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Epoch of Reionization
Galaxies and Quasers begin to form - starting reionization.
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms
Today: Astronomers look back and understand
NASA/WMAP Science Team
Planck
THESEUS
EUCLID

Classification of SN is based on spectral characteristic



I will not speak about spectra

SN Ia: mass overcomes the Chandrasekhar mass, **losses the stability** and start to contract

SN II: main trigger is the **gravitational instability of the iron core.**

PISNe: pairs creation reduces internal pressure and leads to rapid contraction of the star. **An instability regime.**

« The nuclear fire »

- Supernovae are explosive phenomena.

- The most difficult part is the « ignition » and the « propagation of this nuclear fire » inside the star. (Zeldovich 1960, Arnett 1969, Ivanova 1974).

- After ignition, the explosion develops by burning the material. A shock wave is created and develops in the star. The rate at which the wave propagates is characteristic of the type of explosion: detonation (supersonic velocity) or deflagration (sub-sonic). In this type of combustion, the material is burned much faster than in a « classical » flame process.

- We need hydrodynamical calculations to model the propagation of this explosion.

The flame propagation inside stars

The speed of the flame wave can be expressed as:

$$U_L \simeq \sqrt{\frac{D_T}{\tau_{burn}}}$$

*Landau Lifshitz (1958)

Thus, the thickness of the wave can be obtained as:

$$d_L \simeq \frac{D_T}{U_L} = \sqrt{D_T \tau_{burn}}$$

Development of instabilities (as Rayleigh-Taylor and Landau-Darrieus instabilities), will modify the shape of the front-wave increasing the burning rate.

Spatial resolution is $\delta R \sim \frac{R}{N}$ The only processes that can be reproduced are those with $\gg \delta R$.

The thickness of the burning wave is $l \sim 0.1\ cm \ll \delta R$

$\Downarrow$

Regime of burning is assumed and it is incorporated in the explosion.

The fate of massive stars

Main sequence Mass	Core Mass	SN
10<M<95	2<M<40	Fe core collapse
95<M<150	40<M<63	Pulsation instabilities + core collapse
150<M<260	63<M<133	pair instability
M>260	M>133	Black hole

This type of instability was predicted by Rakavy & Shaviv (1967)

Because of the huge mass of the star that encounters pair creation, energy release during PISN explosion is tremendous

Energy released: $\simeq 3.5 \times 10^{52}\ ergs$

to be compared to the binding energy $\simeq 0.5 \times 10^{52}\ ergs$

Bond, Arnett and Carr (1984)

Role of temperature

When central temperature in the core of the star reaches a few 10ˆ9 K : possibility of pair creation

Planck spectrum

Wien Law

$$\lambda_{max} T = 0.2898 \ cm.K$$

$$E_\gamma \simeq 1 \ MeV \qquad\qquad T \simeq 2 \times 10^9 \ K$$

First computations: Koppe (1948),

See also: Fowler & Hoyle (1964)

For massive stars, they reach high value of T at relatively **low value of central density**

This can be understood by some basic equations of standard stellar physics

$$\rho_c \simeq \frac{T_c^3}{M^2}$$

(formulation of Fowler and Hoyle $\rho_c \simeq \frac{T_c^3}{M^{1/2}}$)

Example of typical central density : few 10^5 g.cm-3

Effect of pair creation

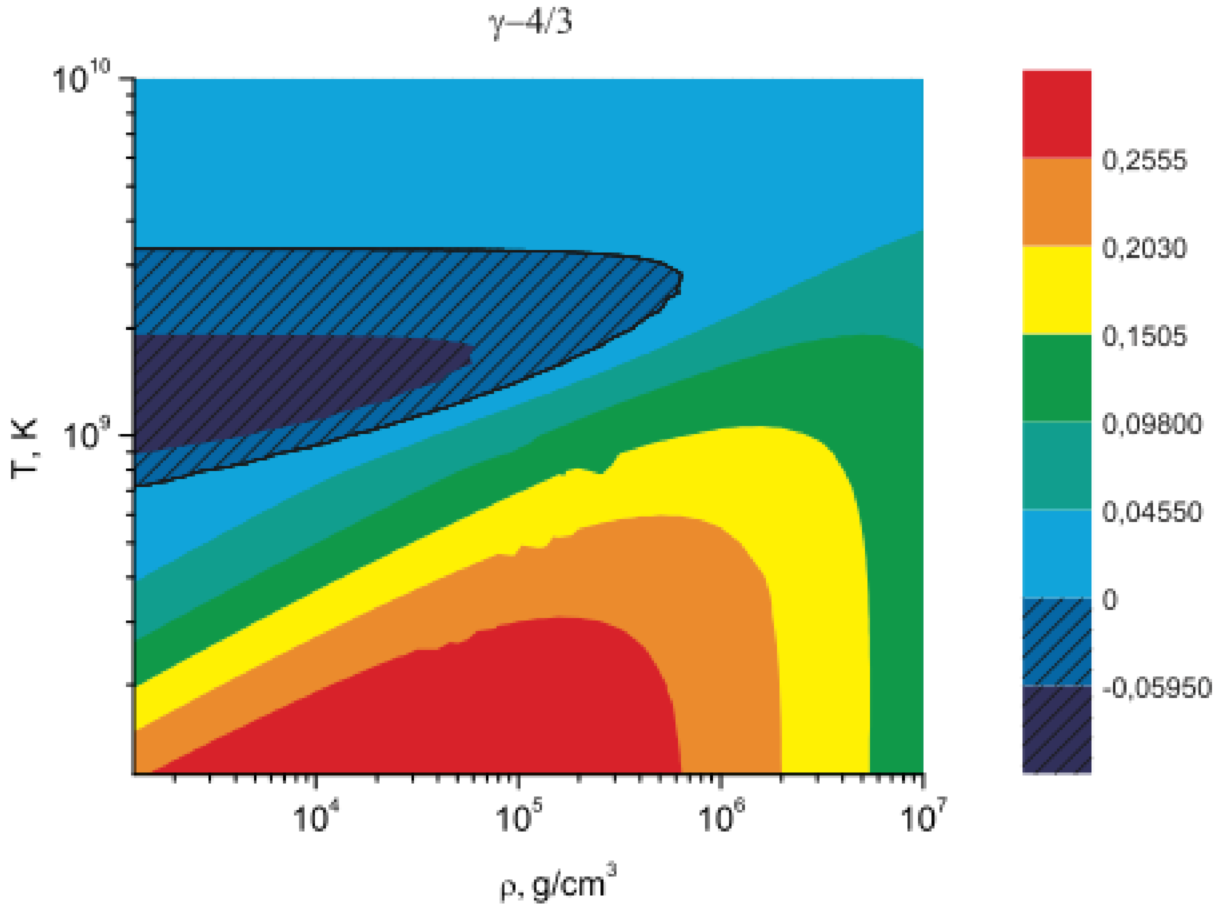
Fowler and Hoyle discovered that when the central temperature of a star reaches value 2 10^9 K, intensive pair creation occurs.

the consequence is to increase the energy losses by neutrinos

$$e^{+} + e^{-} \rightarrow \nu_e + \nu_e$$

This accelerate the contraction of the star and rise the temperature and create new pairs.

Model of Pair-instability SN



Absorption of energy to create rest mass of the pairs
When a sufficient amount of the star entered in this area it becomes
dynamically unstable

A recent history

The first evolutionary calculations were performed by Rakavy and Shaviv (1967). Computation of a 30 solar oxygen core.

The first dynamical computation of explosion was performed by Barkat et al. (1967): 40 solar mass oxygen core. They have found the limit of mass for PISNe of 30 solar mass oxygen core.

First detailed evolution of helium core were performed by Arnett (1972). He demonstrated that the core were composed mainly of oxygen when reaching the pair instability zone.

El Eid et al (1983) have studied evolution of 80-500 solar mass.

Glatzel et al (1985) have studied the effect of rotation. This could extend the region of mass

Woosley & Heger (2002) The evolution and explosion of massive stars

Woosley,Blinnikov, Heger (2007) SN 2006gy

also Binsnovatyi-Kogan, Nomoto, Gal-Yam

Yusof et al (2013) Evolution and fate of very massive stars

KEPLER code: Woosley CASTRO code Almgren et al

MESA code: Paxton et al 2010, 2013

Multidimensional simulations: Chen et al. 2011,Joggerst et Whalen 2011

Simulation setup

- Computational Grid
- Initial Model
- Equation of State
- Simulation runs

To investigate the behavior of pair-unstable stars we performed various hydrodynamical simulations using:

FOR 1D SIMULATIONS:

1D Lagrangian code

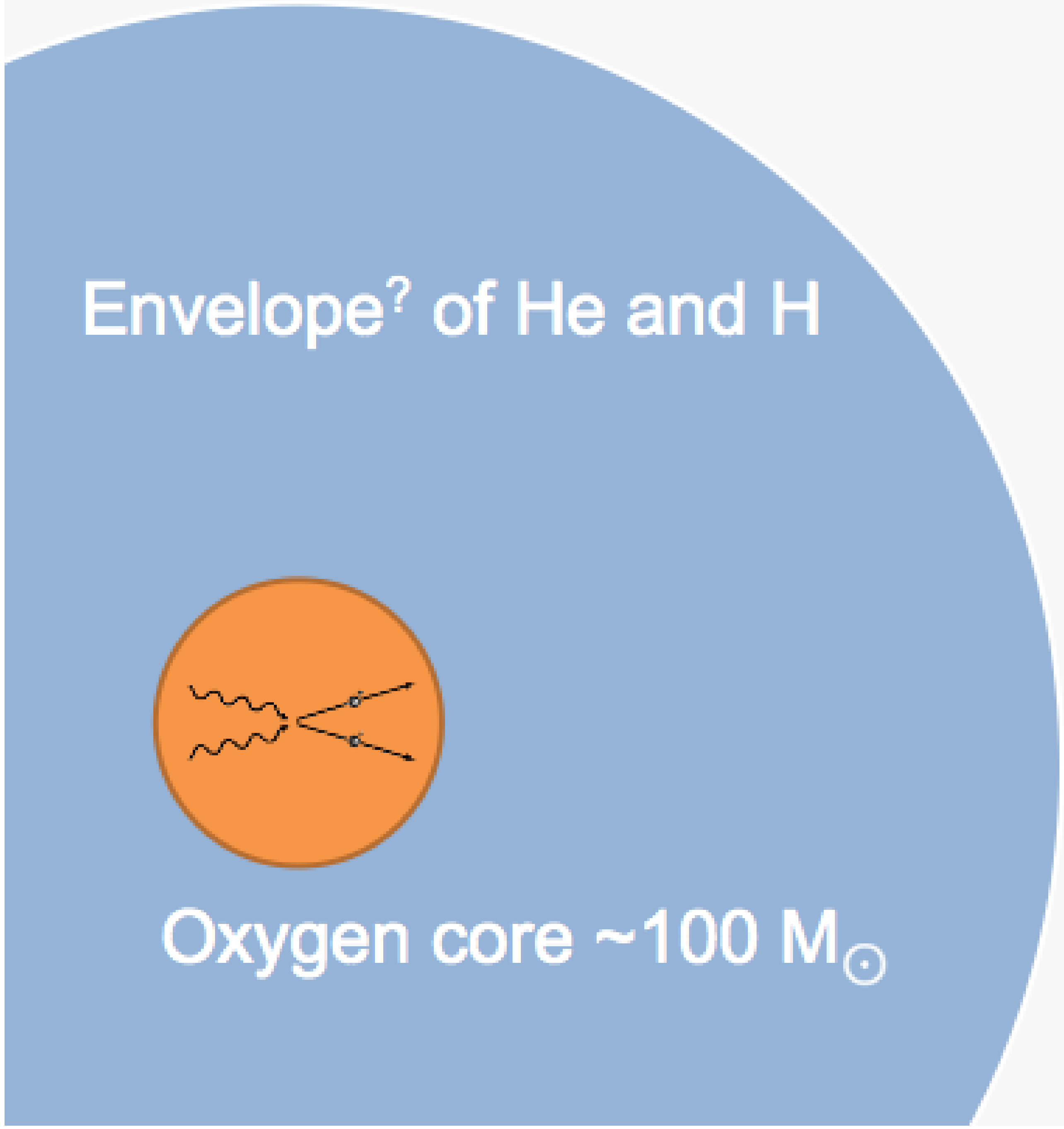
Aim: study the fate of oxygen cores depending on mass and initial configuration

FOR 2D SIMULATIONS:

Piecewise parabolic method on a local stencil

Aim: to study the last stage of explosion when shockwave propagates outward

Numerical simulations



- Spherical symmetry
- Computation of the core only
- Polytrope with $\gamma=4/3$

  $P=K\rho^{\gamma}$

Numerical simulations

$$
\begin{cases}
\partial r/\partial t = v \\
\partial v/\partial t = -Gm/r^2 - 4\pi r^2(\partial P/\partial m) \\
\partial T/\partial t = \left[- 4\pi \dfrac{\partial(r^2 v)}{\partial m}(T(\partial P/\partial T)_\rho) + \varepsilon_{\text{nucl}} - \varepsilon_\nu\right] / (\partial E/\partial T)_\rho
\end{cases}
$$

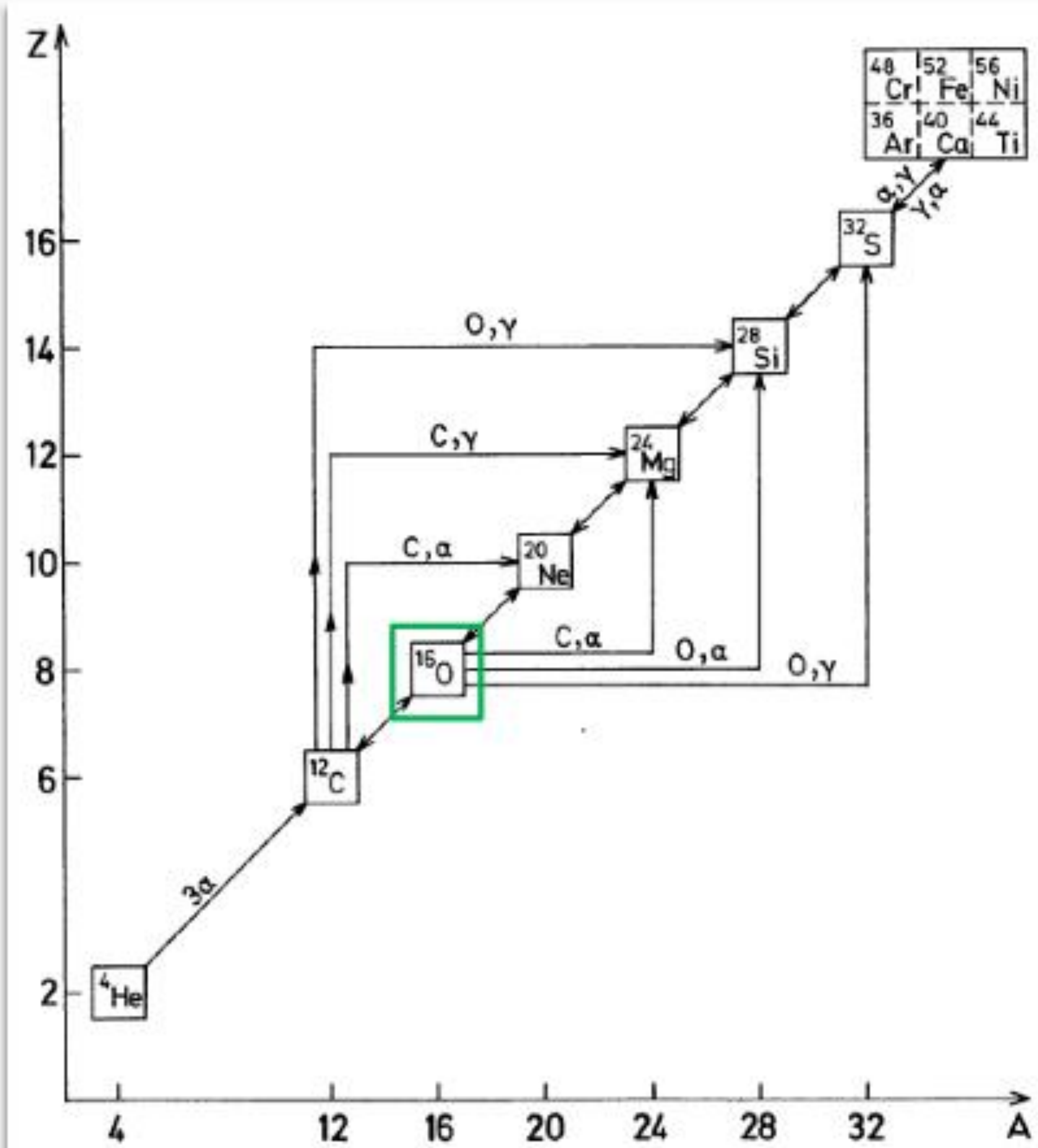
Nuclear burning

Neutrino losses

System of equations

$$\begin{cases} \partial r/\partial t & = v \\ \partial v/\partial t & = -Gm/r^2 - 4\pi r^2(\partial P/\partial m) \\ \partial T/\partial t & = (-4\pi \frac{\partial(r^2 v)}{\partial m} T(\partial P/\partial T)_\rho + \varepsilon_{nucl} - \varepsilon_\nu)/(\partial E/\partial \rho)_\rho \\ P(\rho, T, Y_i) & = EOS(\rho, T, Y_i) \\ ... & \\ dY_j/dt & = Y_k Y_l \rho R_{jk,l} - Y_j Y_l \rho R_{jl,m} + Y_i \lambda_{i,j} - Y_j \lambda_{j,k} \\ ... & \end{cases}$$

Nuclear reactions

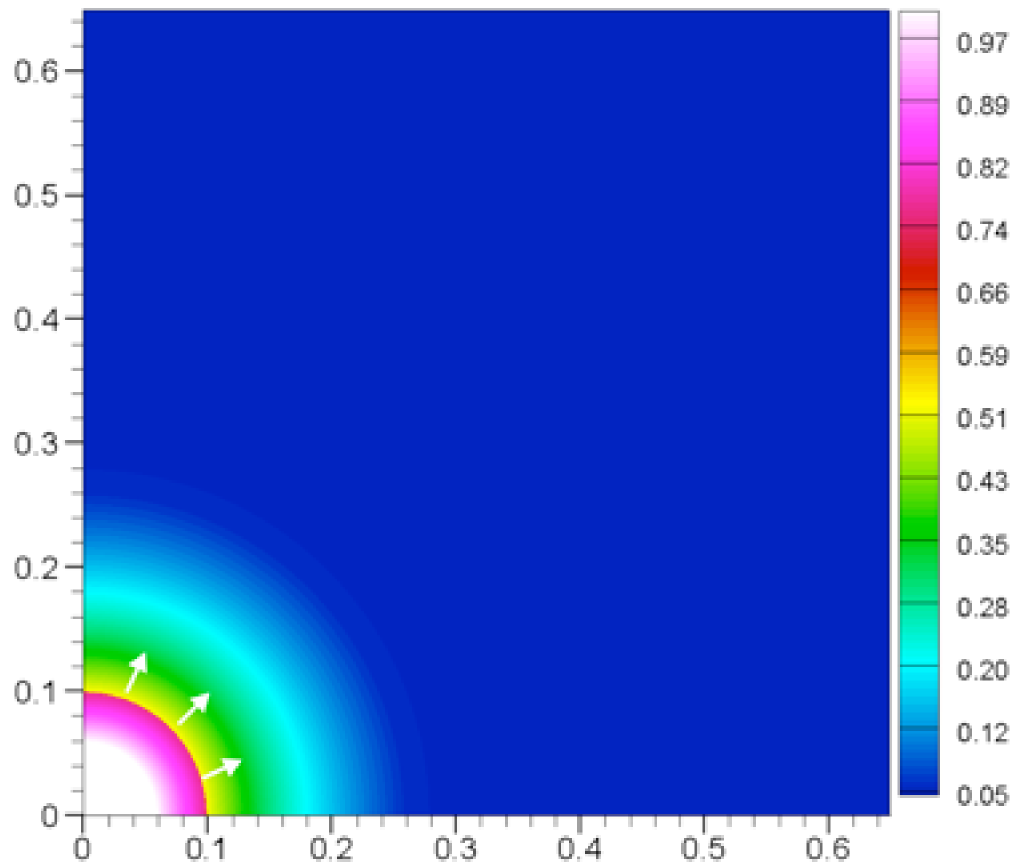


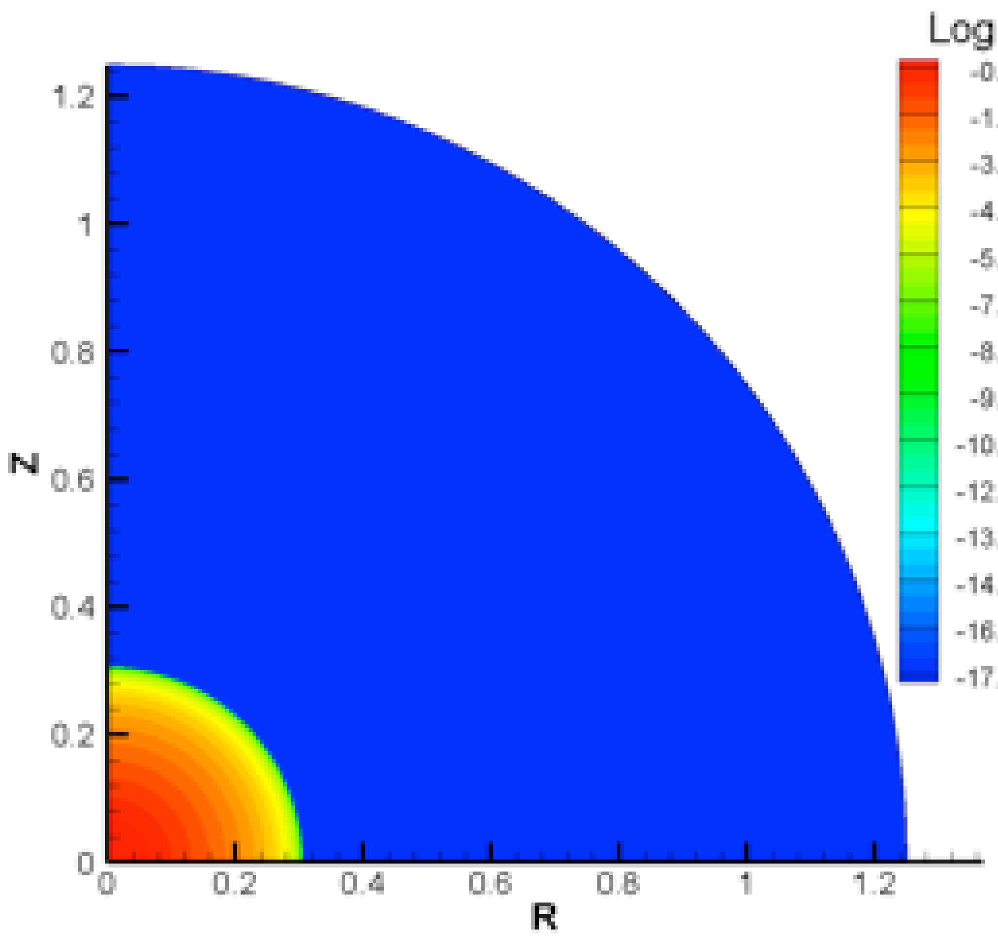
Multidimensional approach

- Oxygen core : 100 solar mass
- Radius of the core : 0.3 solar radius
- Central density : $\rho_c \sim 2 \times 10^5 g/cm^{-3}$
- Central Temperature : $Tc \sim 2 \times 10^9 K$

Hydrodynamics simulations were performed with a numerical code based on PPML algorithm Popov & Ustyugov (2007); Popov (2012)

Initial conditions



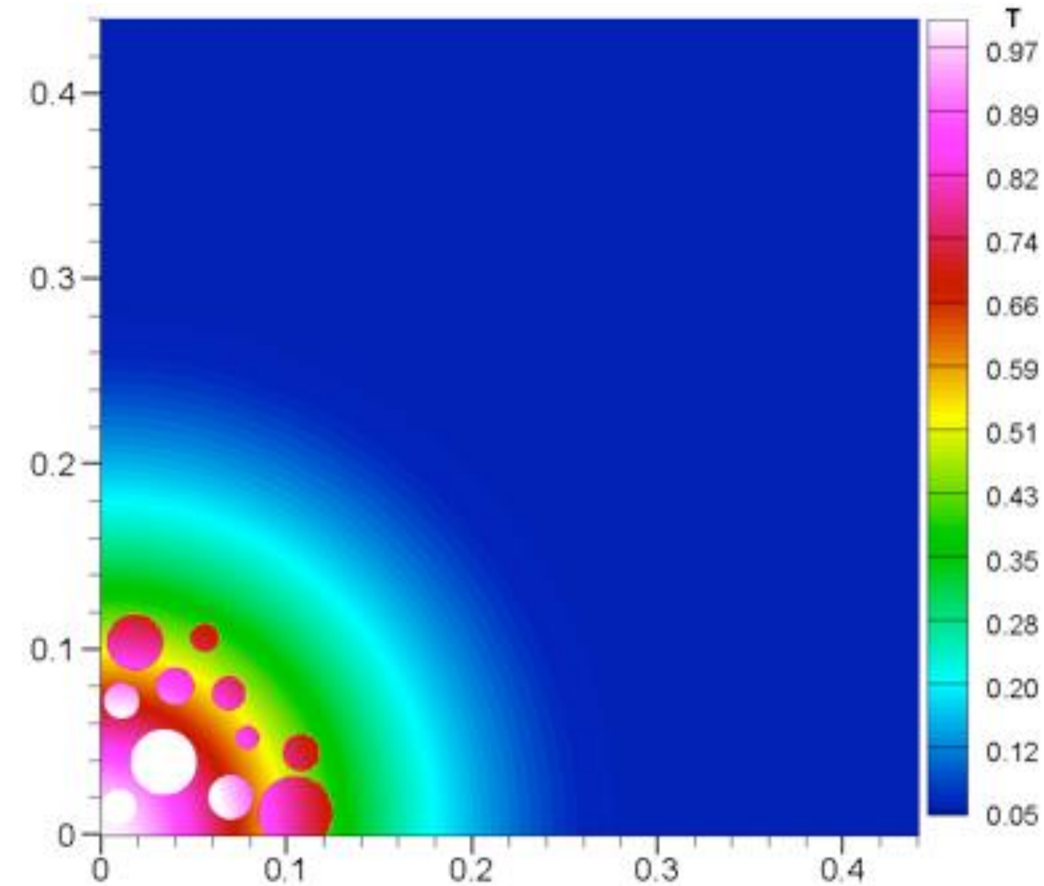


The energy 5. 10^52 ergs was deposited in the central region . This region contains 60 solar mass.

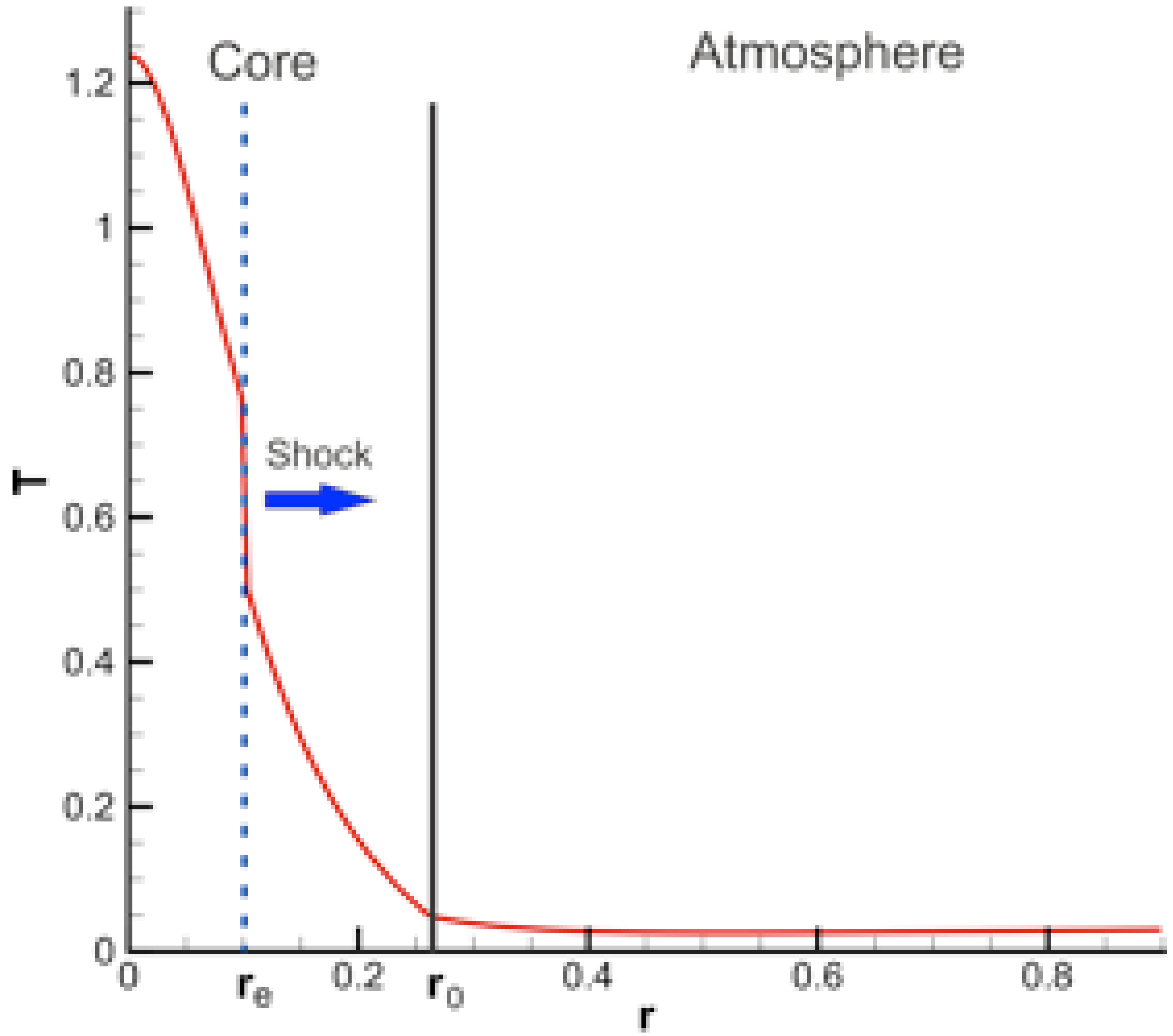
The pictures were obtained with 2D PPML code in cylindrical geometry (r,z) on 1600 1600 grid.

Multi-explosion core

- The fragmentation could be related with instabilities of the burning front.
- The front could propagate in different directions with different velocities. If there are some inhomogeneities in density, for example, some dense fragments in the central core, they could give several ignition points.
- Explosion was set by 11 ignition areas, which were distributed randomly. Total energy inserted into these areas is 5. 10^52 ergs



Nuclear burning in the center of a star could cause the development of large-scale convection (Arnett 2011) if convention occurs prior the moment of pair instability the contraction and explosion could be non symmetrical. Inhomogeneities in T and rho could cause ignition of spots to occur in the core.

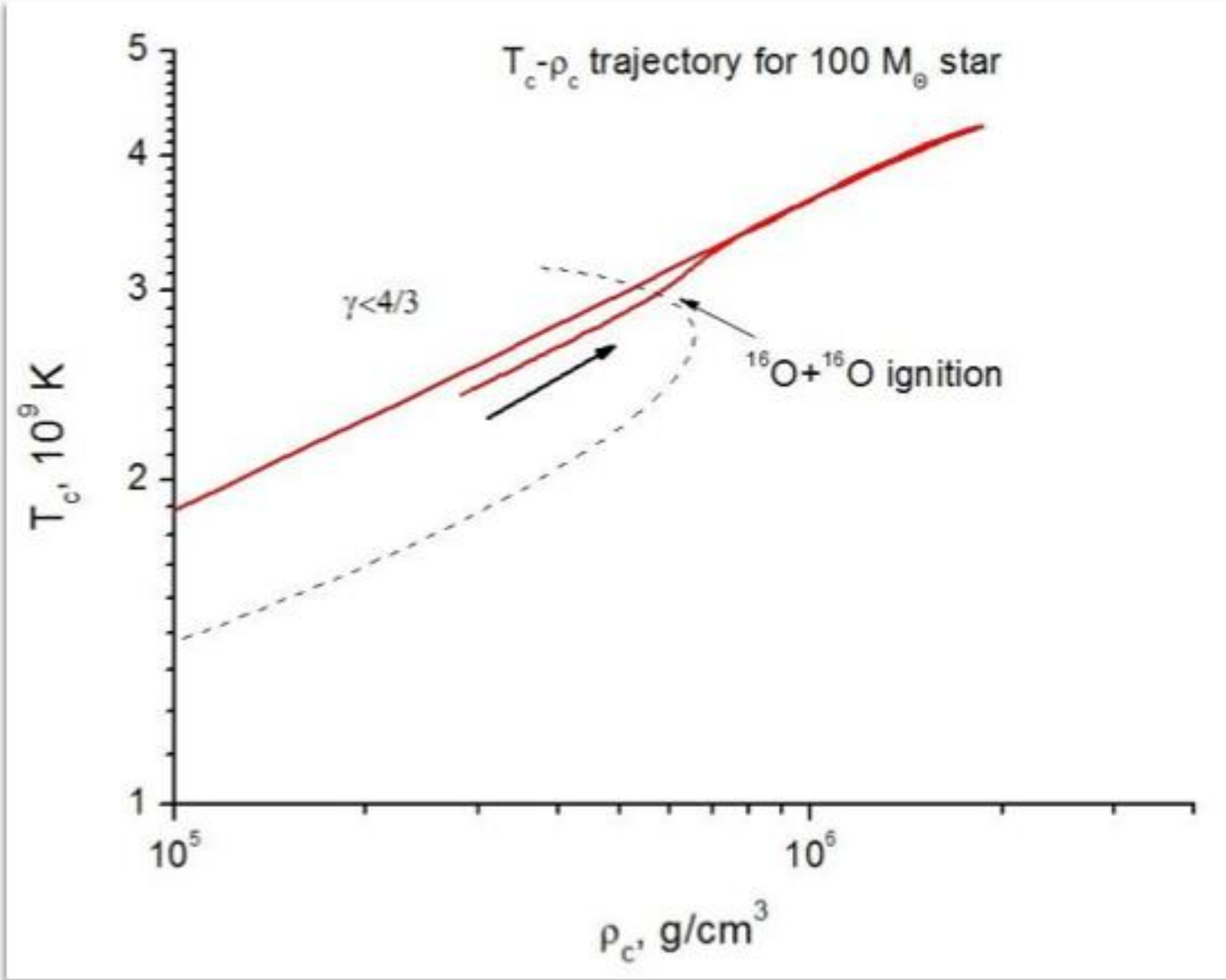


The energy deposition, which produces the shock, is shown
Temperature profile at the moment of explosion in the units of 2.36 10**9K
The values for the atmosphere: order of 10**8 K

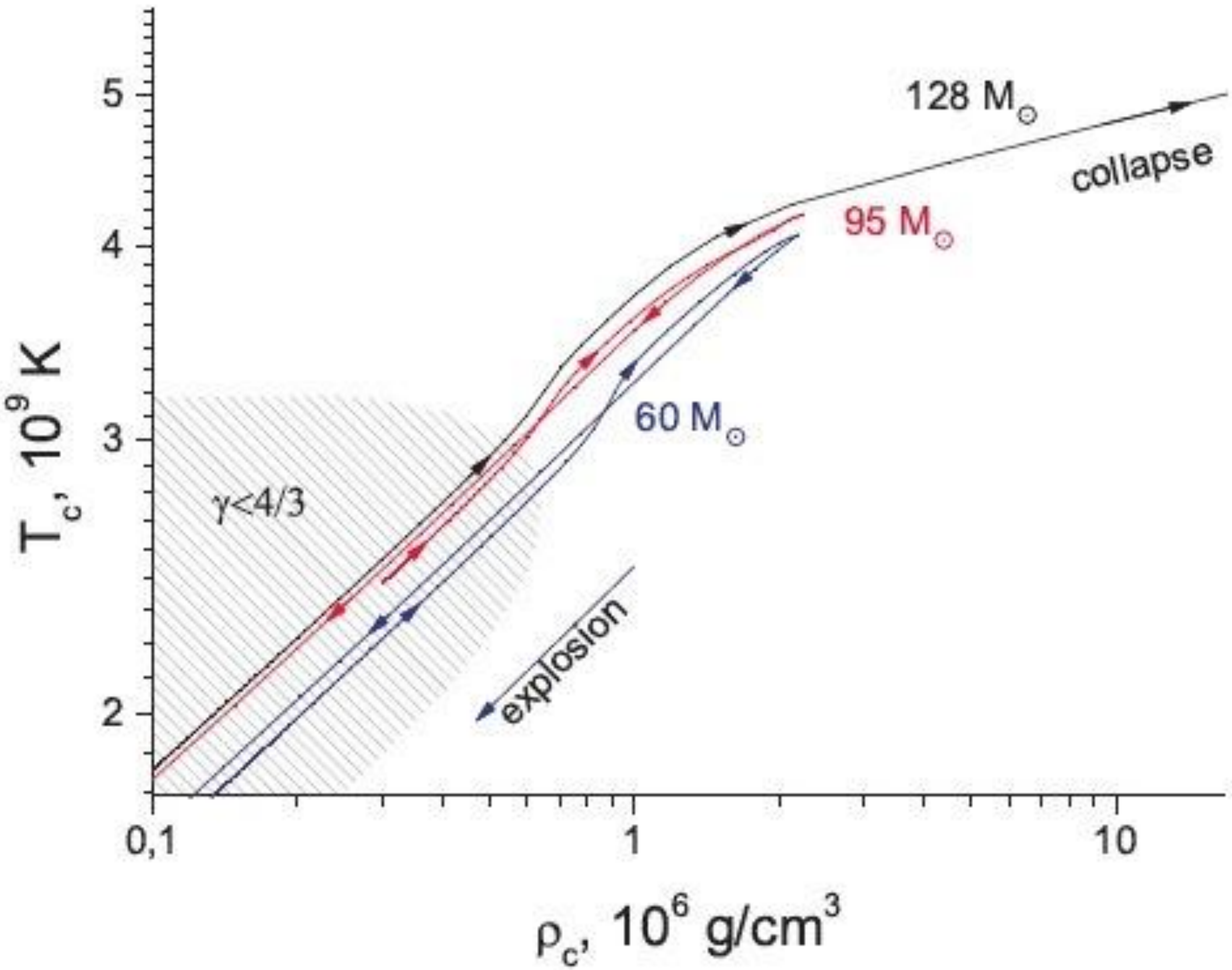
Results

- 1D code: dynamical evolution
- Scaling relation between Enuc and T
- 2D code: symmetrical explosion
- 2D code : multicore explosion. Fragmentation of the core

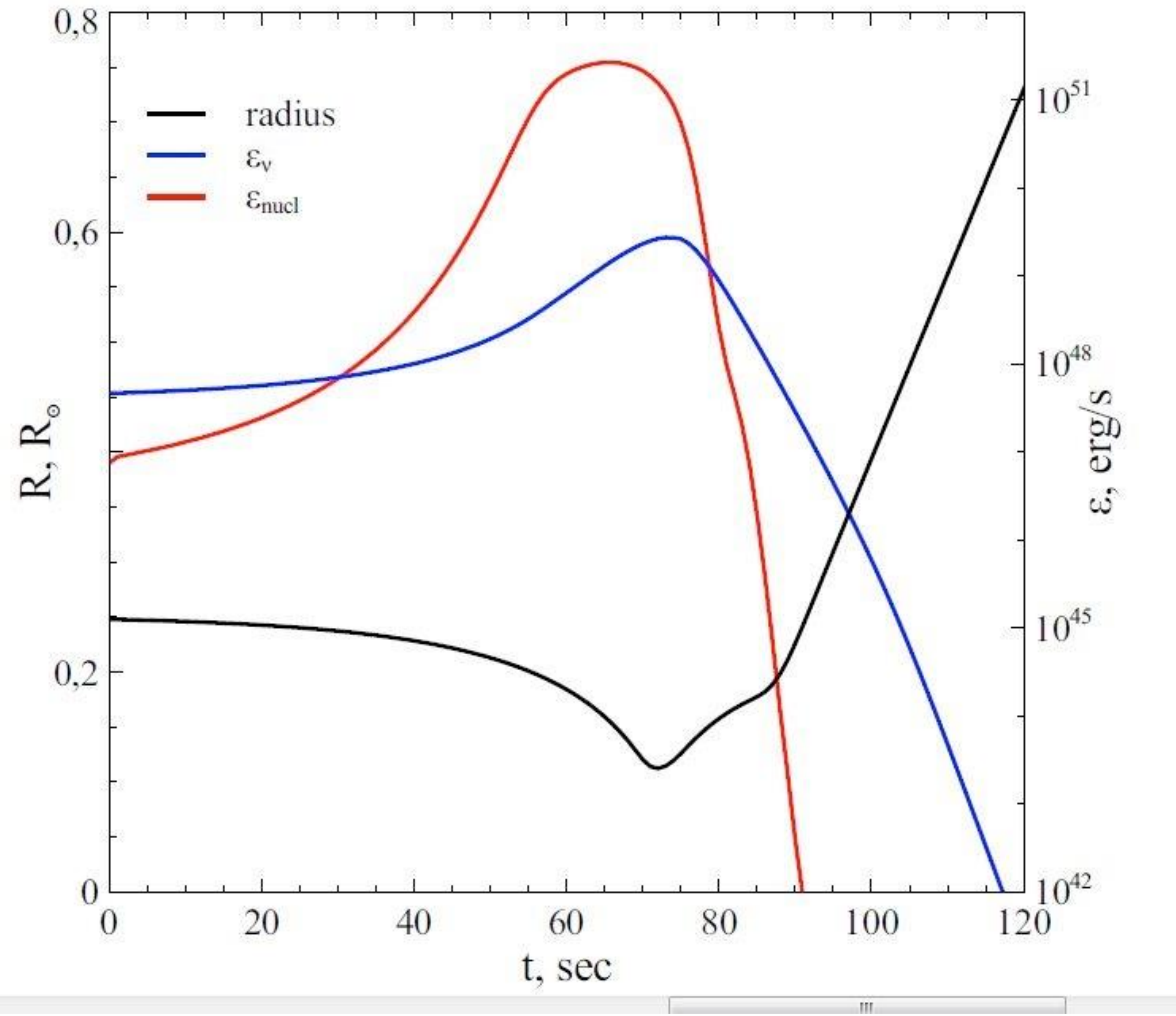
Results



T_c-ρ_c trajectory for 100 $M_\odot$ star
γ<4/3
$^{16}O+^{16}O$ ignition
T_c, 10^9 K
ρ_c, g/cm^3
5
4
3
2
1
10^5
10^6

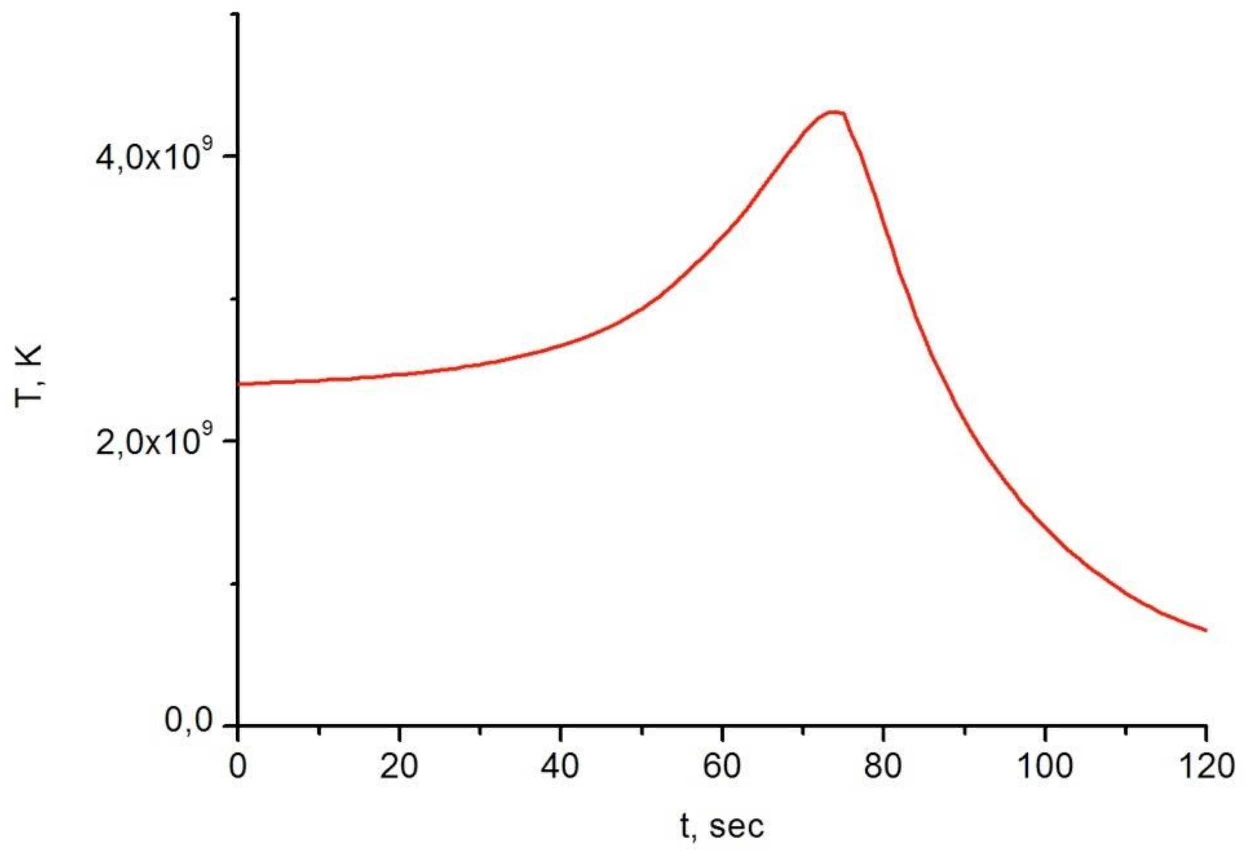


T_c, 10^9 K
5
4
3
2
128 $M_\odot$
collapse
95 $M_\odot$
60 $M_\odot$
γ<4/3
explosion
0,1
1
10
ρ_c, 10^6 g/cm^3

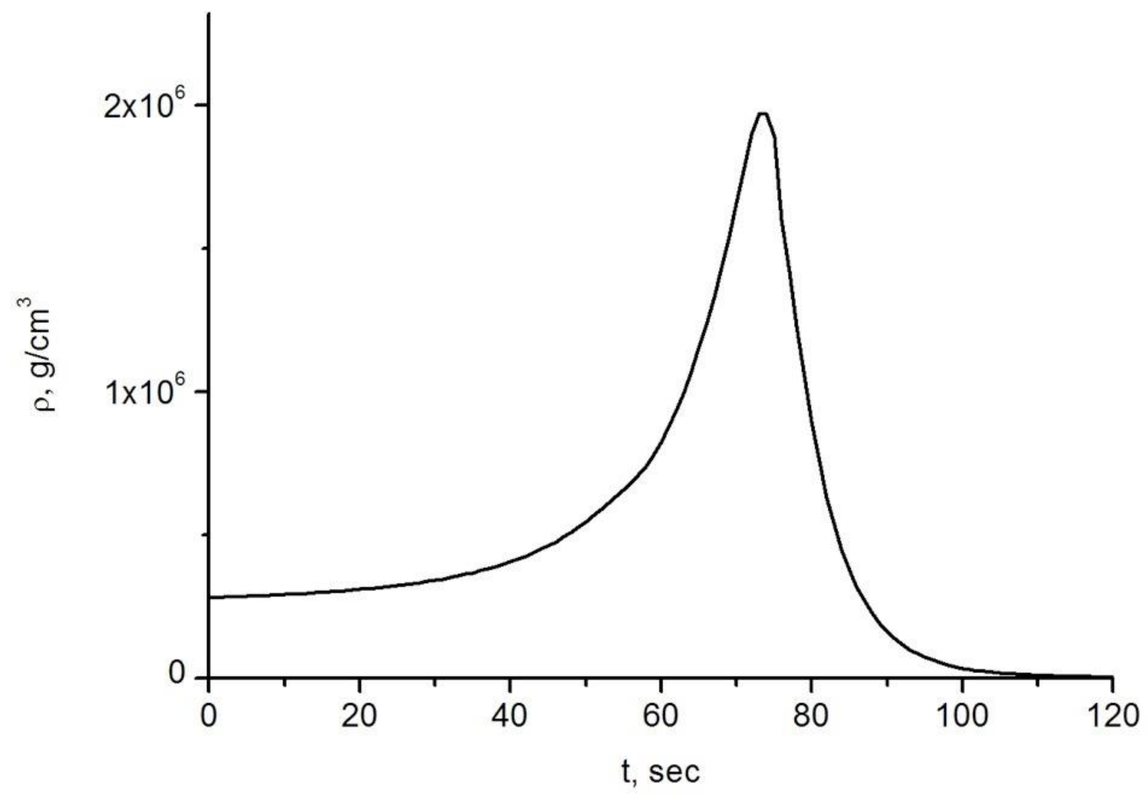

0,8
0,6
0,2
0
R, R⊙
radius
εν
εnucl
10^51
10^48
10^45
10^42
ε, erg/s
0
20
40
60
80
100
120
t, sec

Results: density – temperature

Central temperature

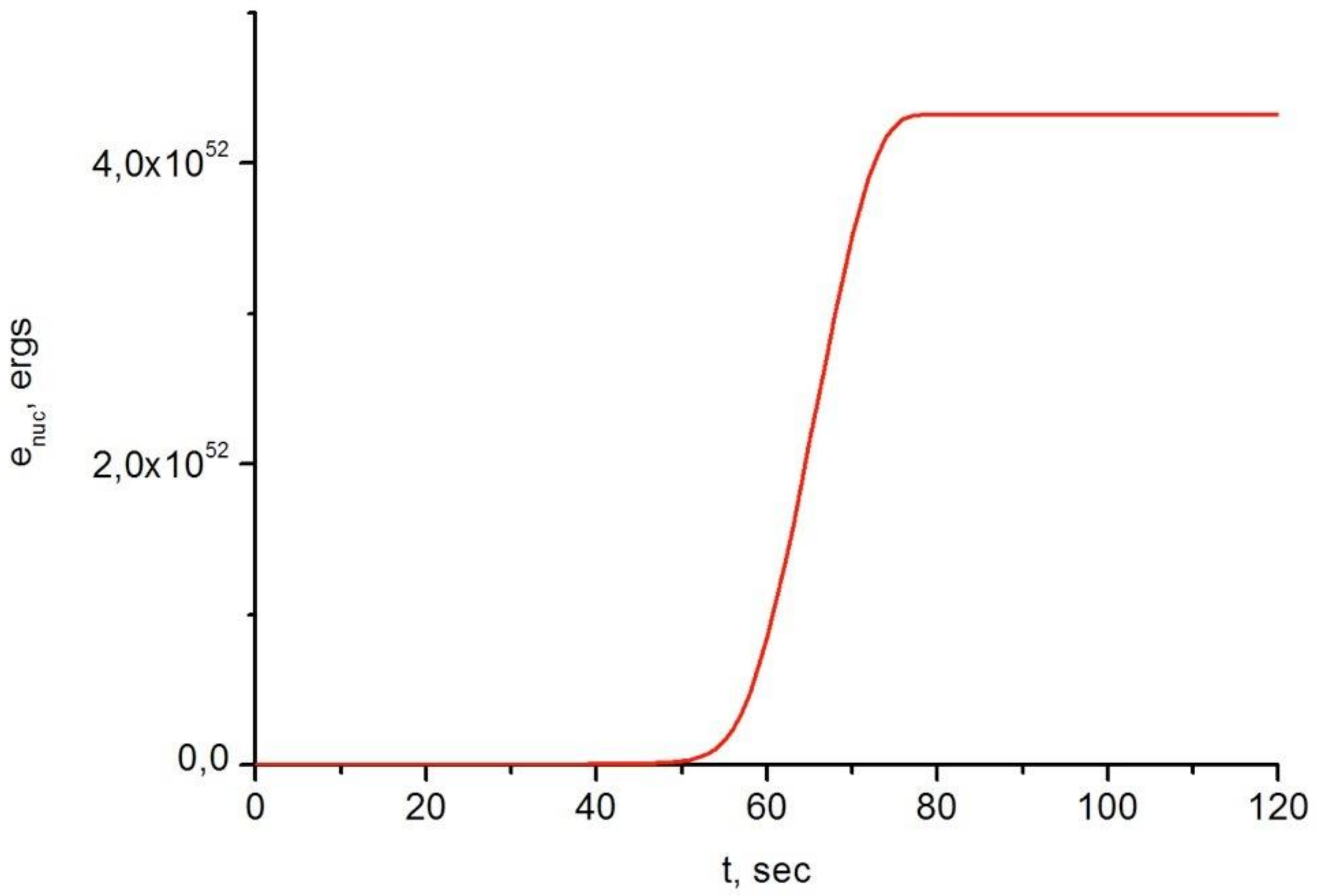


Central density



Results: timescale

Nuclear burning energy



$M/M_\odot$	$\rho_c, 10^5 g/cc$	T_{max}, keV	$E_{nucl}, 10^{52}$ ergs	fate
60	0.87	352	2.23	explosion
60	1.15	351	2.25	explosion
78	0.60	—	—	collapse
78	2.00	—	—	collapse
78	3.00	330	2.46	explosion
100	1.00	—	—	collapse
100	1.65	—	—	collapse
100	2.00	—	—	collapse
100	2.25	—	—	collapse
100	2.40	463	5.11	explosion
100	2.50	421	4.80	explosion
100	2.65	371	4.12	explosion
112	1.00	—	—	collapse
112	1.50	—	—	collapse
112	2.00	470	5.46	explosion
125	1.00	—	—	collapse
125	1.50	—	—	collapse

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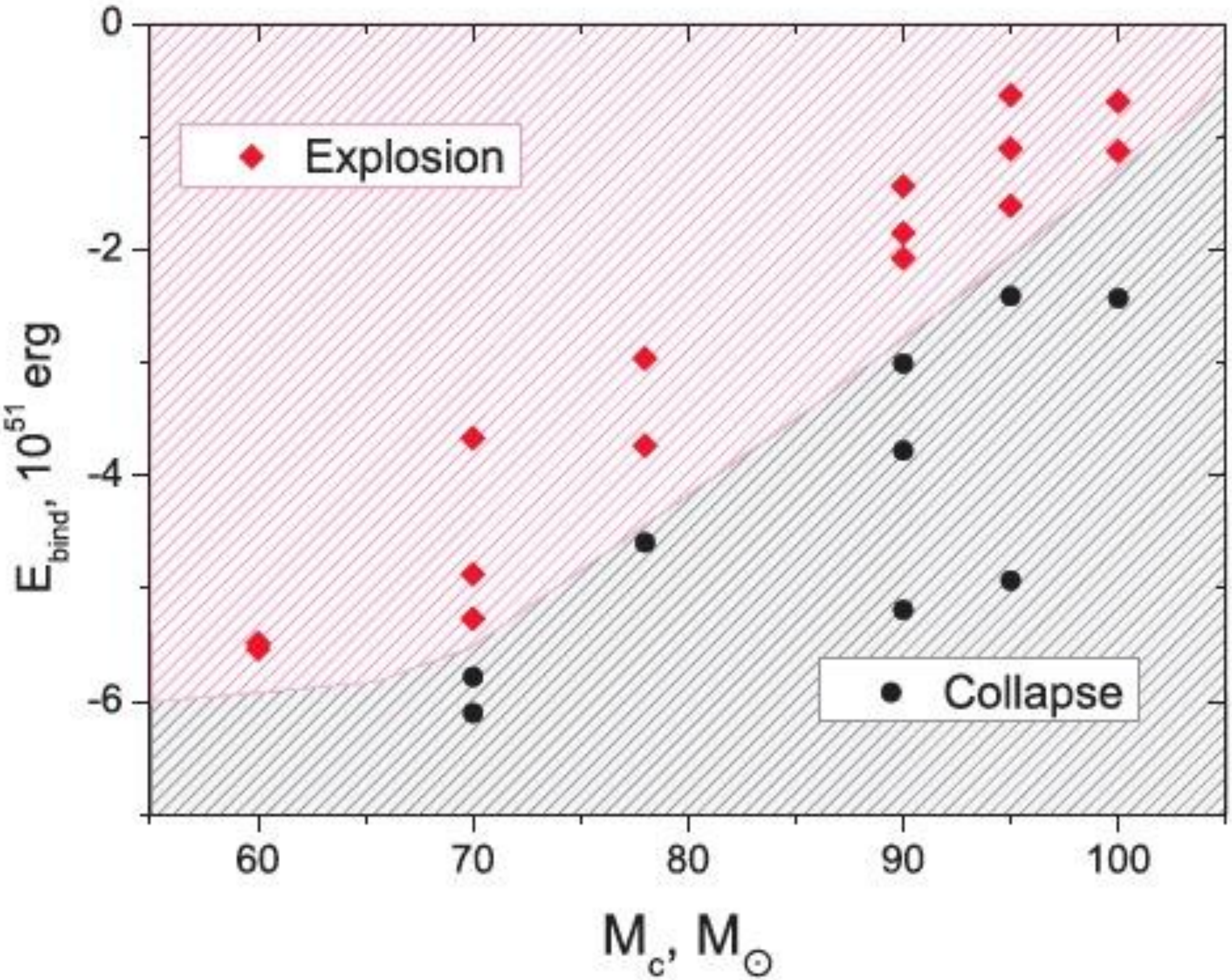
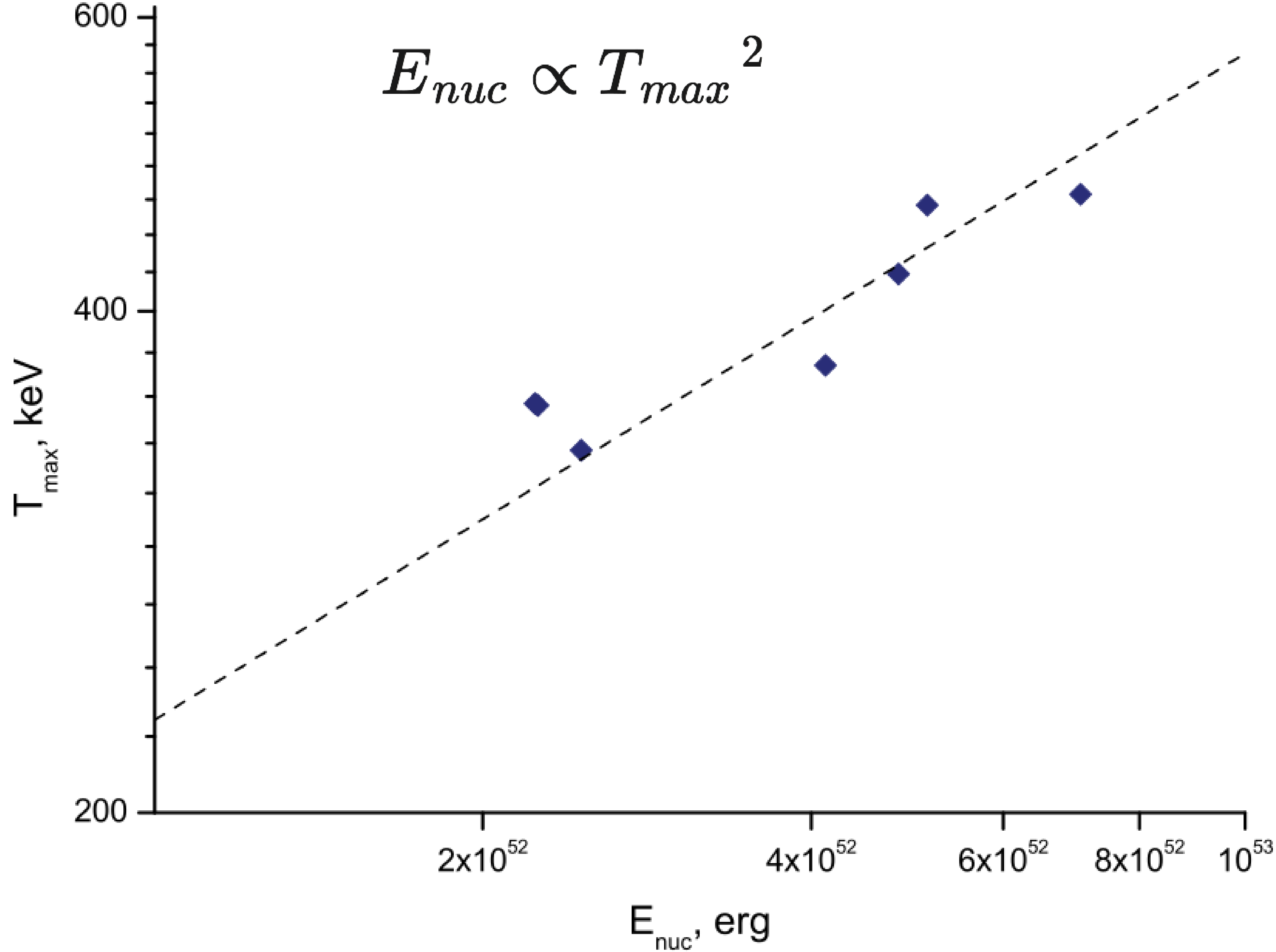


Explosion
Collapse
0
-2
-4
-6
60
70
80
90
100
E_{bind}, 10^{51} erg
M_c, $M_\odot$



$E_{nuc} \propto T_{max}{}^2$
600
400
200
T_{max}, keV
2x10^52
4x10^52
6x10^52
8x10^52
10^53
E_{nuc}, erg

Since source of energy is nuclear burning

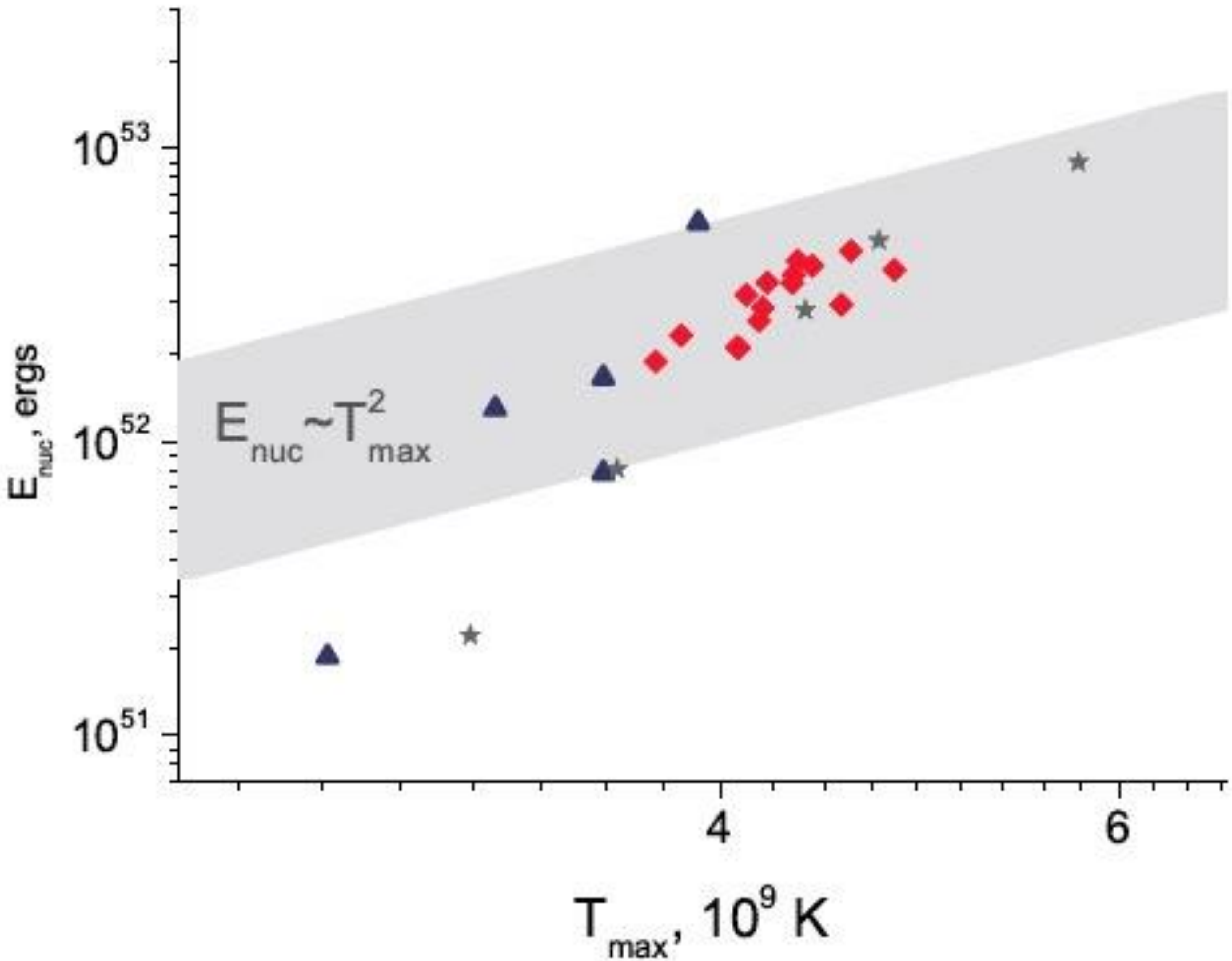
$$L \sim E_{Nucl} \sim M \cdot q, \quad [q] = \frac{ergs}{g \cdot s}$$

$$\frac{dT}{dR} = \frac{3\kappa\rho L}{16\pi a c T^3 R^2}$$

$$\frac{dT}{dR} \rightarrow \frac{T}{R}, \quad \rho \rightarrow \frac{M}{R^3}$$

$$T^4 \sim \frac{ML}{R^4} \sim E_{Nucl}^2$$

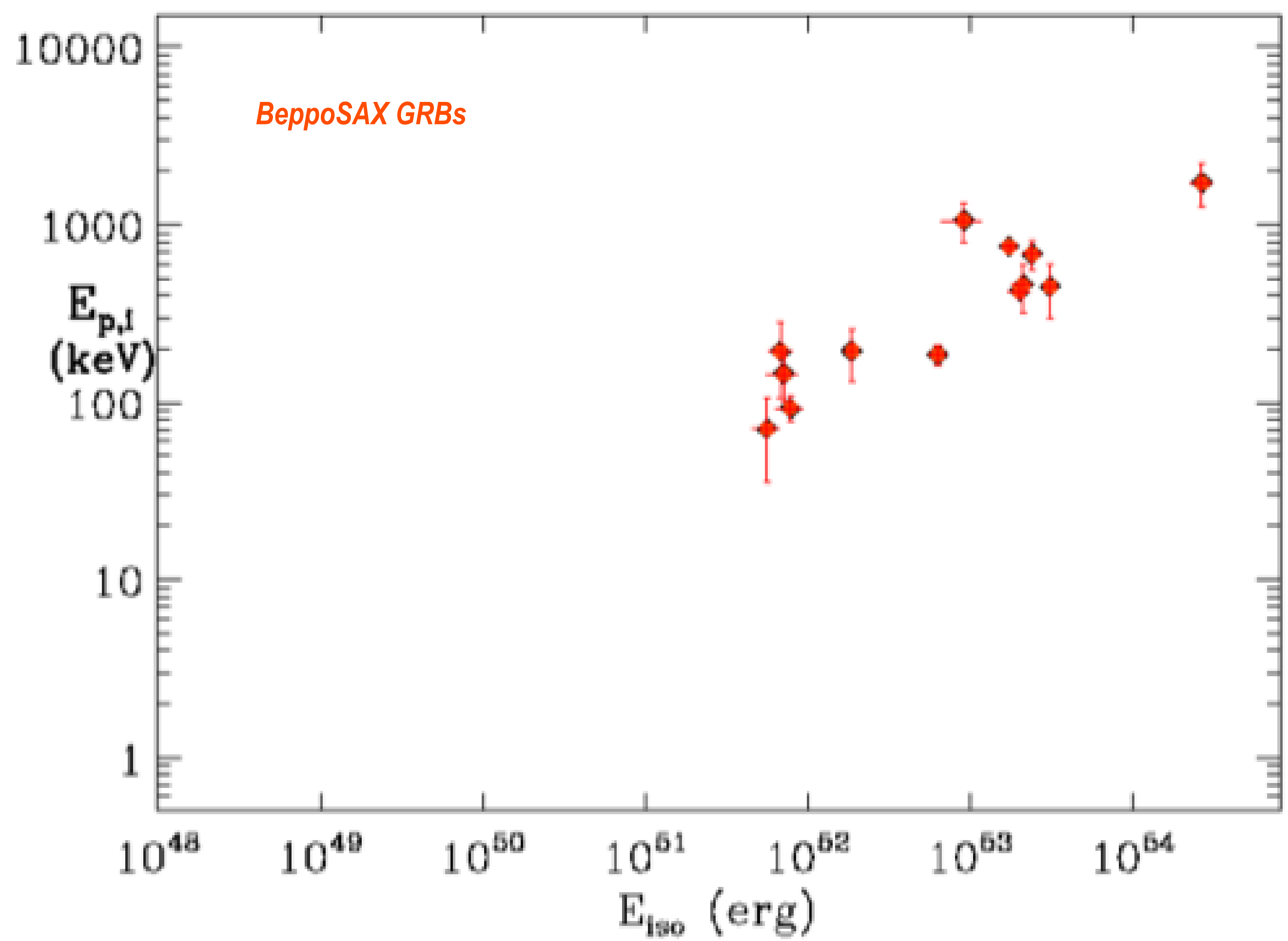
$$\boxed{T^2 \sim E_{Nucl}}$$



10^53
10^52
10^51
E_nuc, ergs
E_nuc~T^2_max
4
6
T_max, 10^9 K

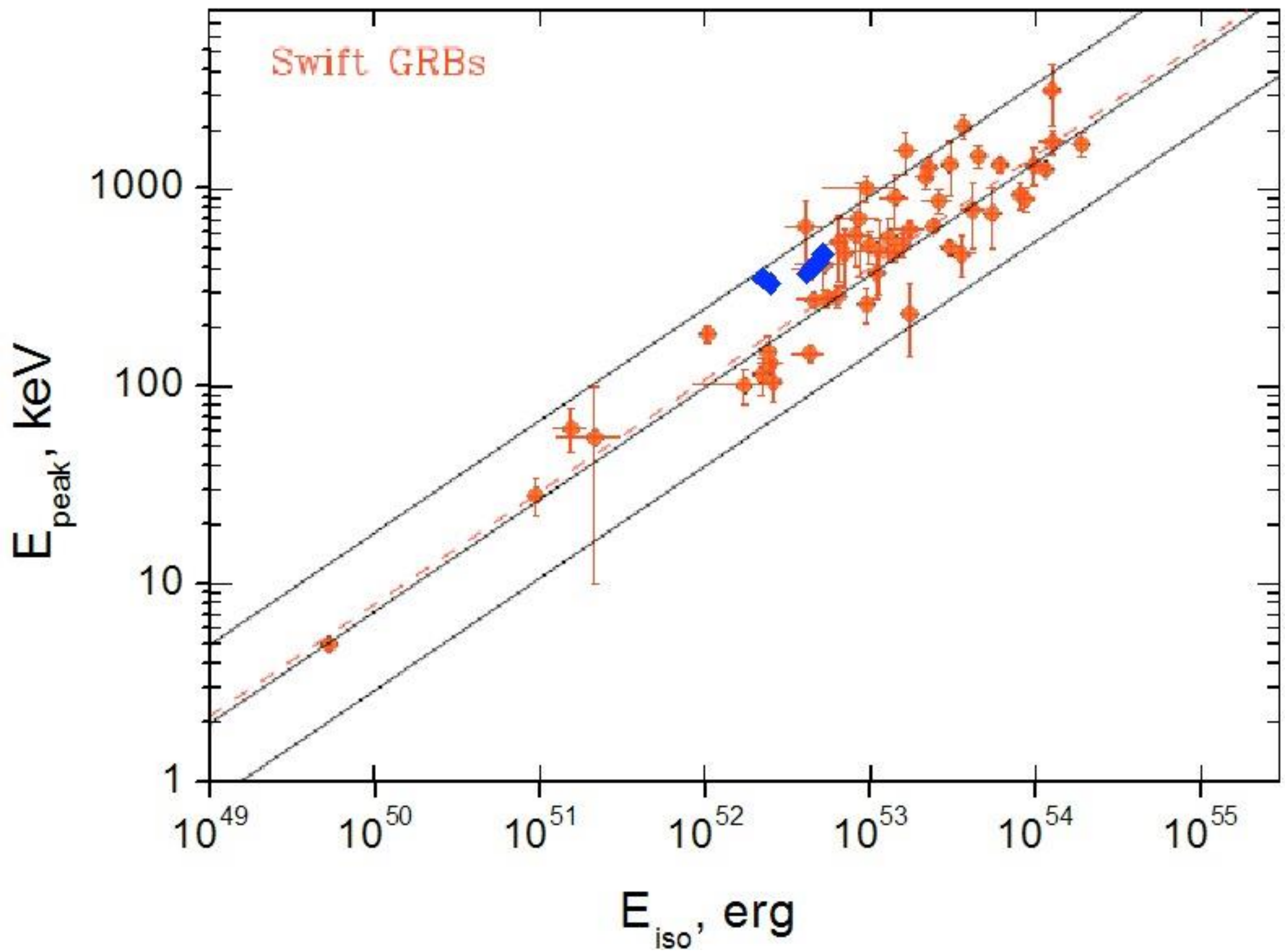
T_{max}

Amati et al. (A&A 2002)

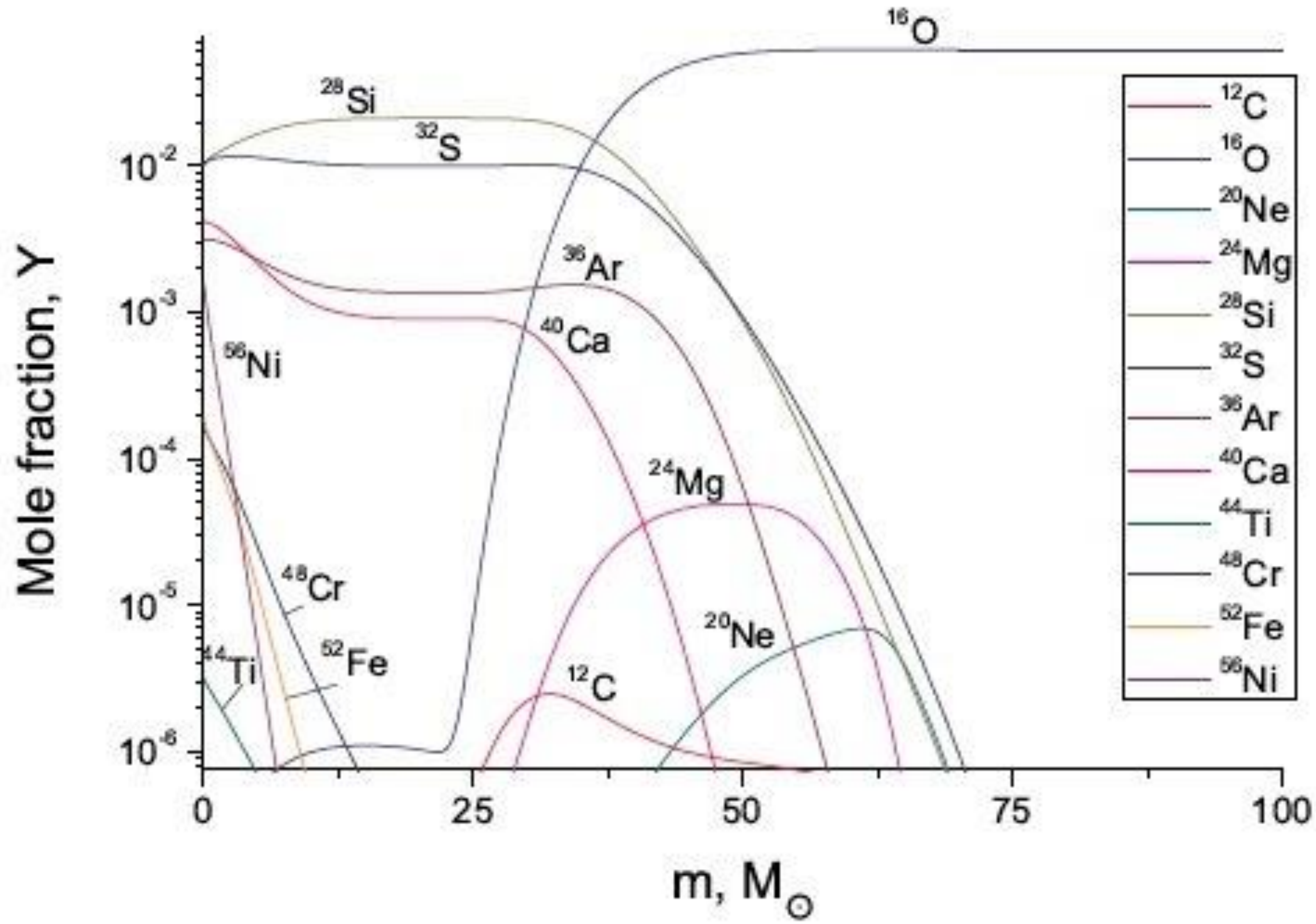


E_{nuc}

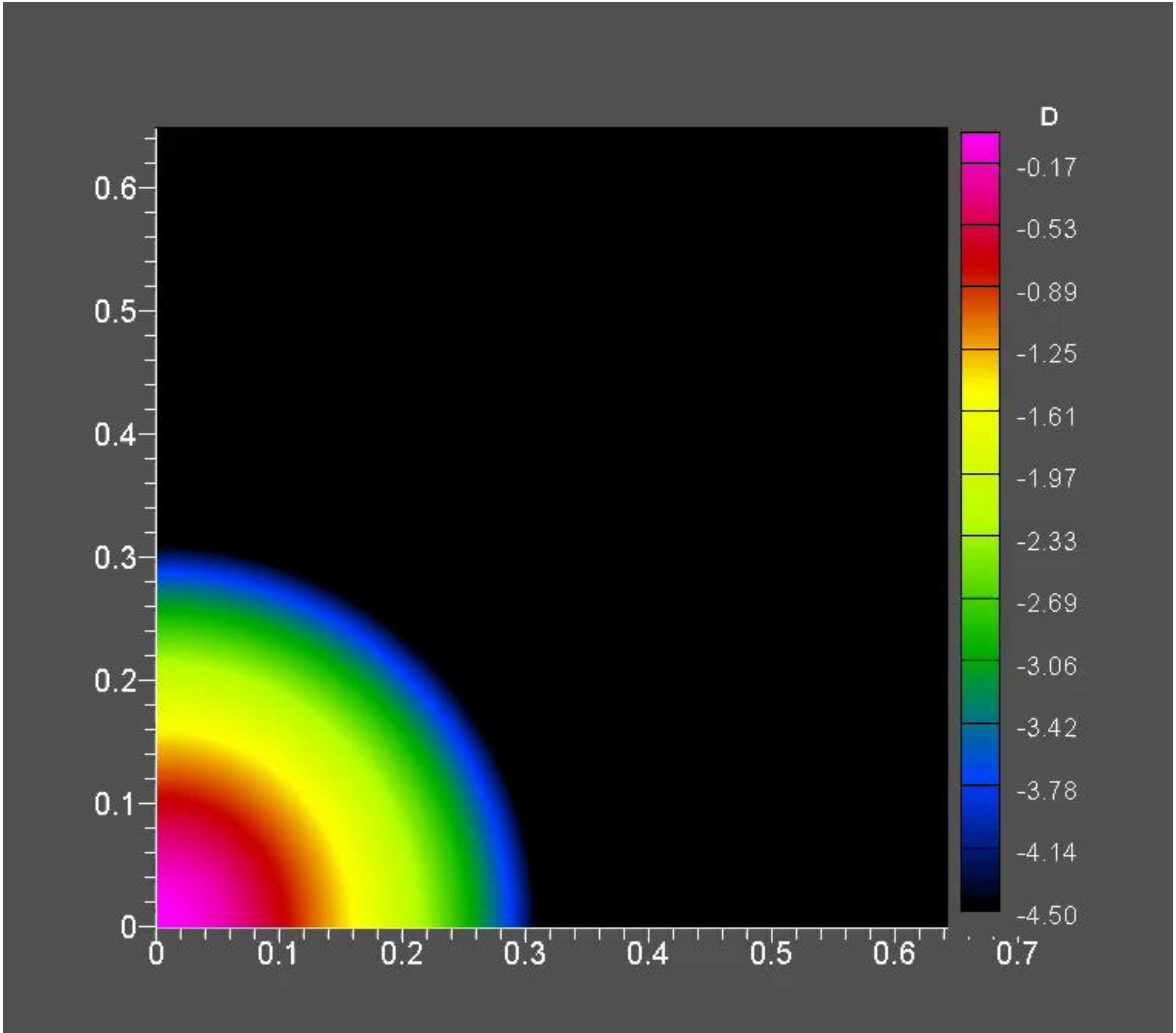
Amati Relation: $E_{nucl} \propto {T_c}^2$

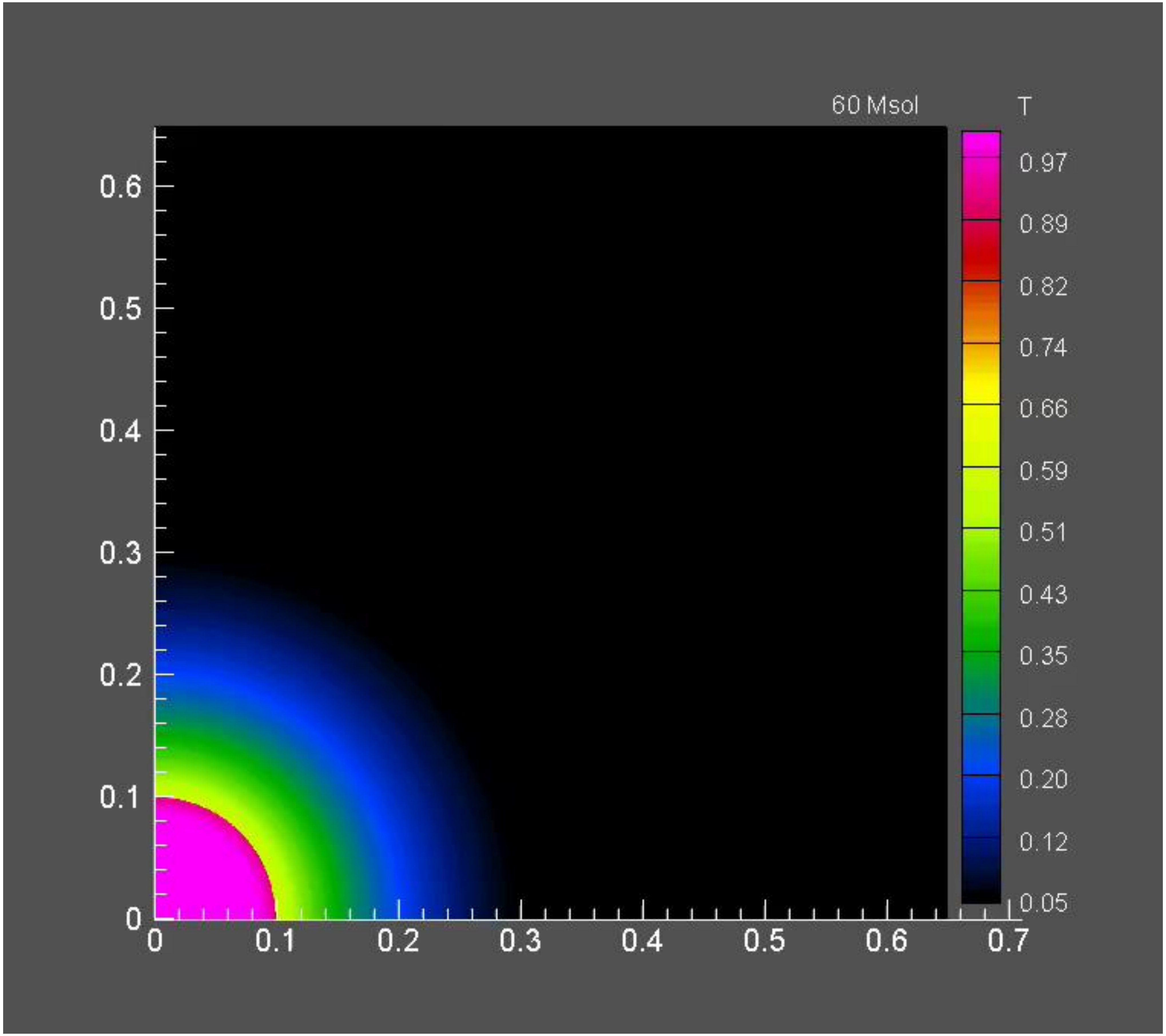


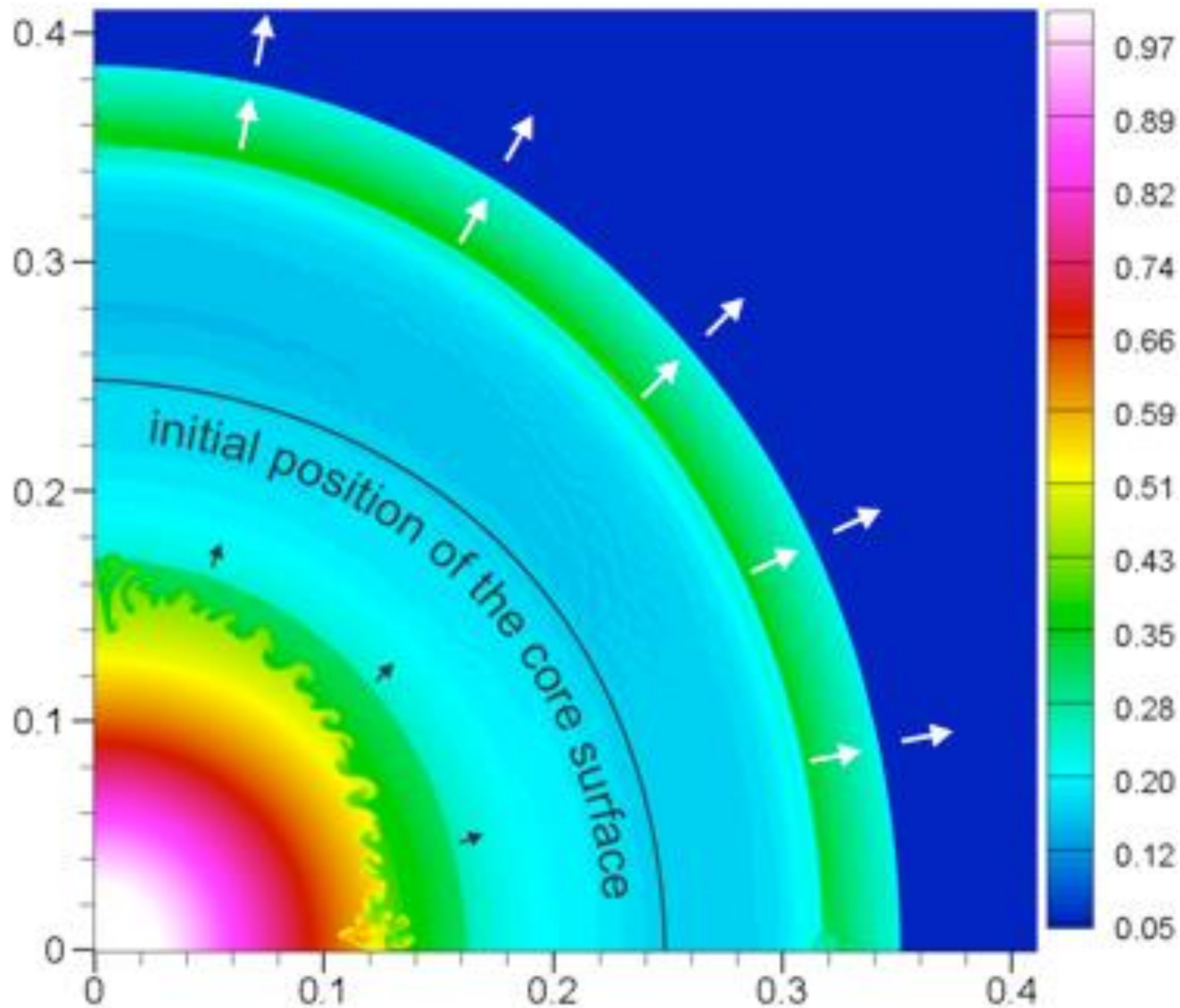
Amati relation from [L. Amati, F. Frontera and C. Guidorzi, 2009]



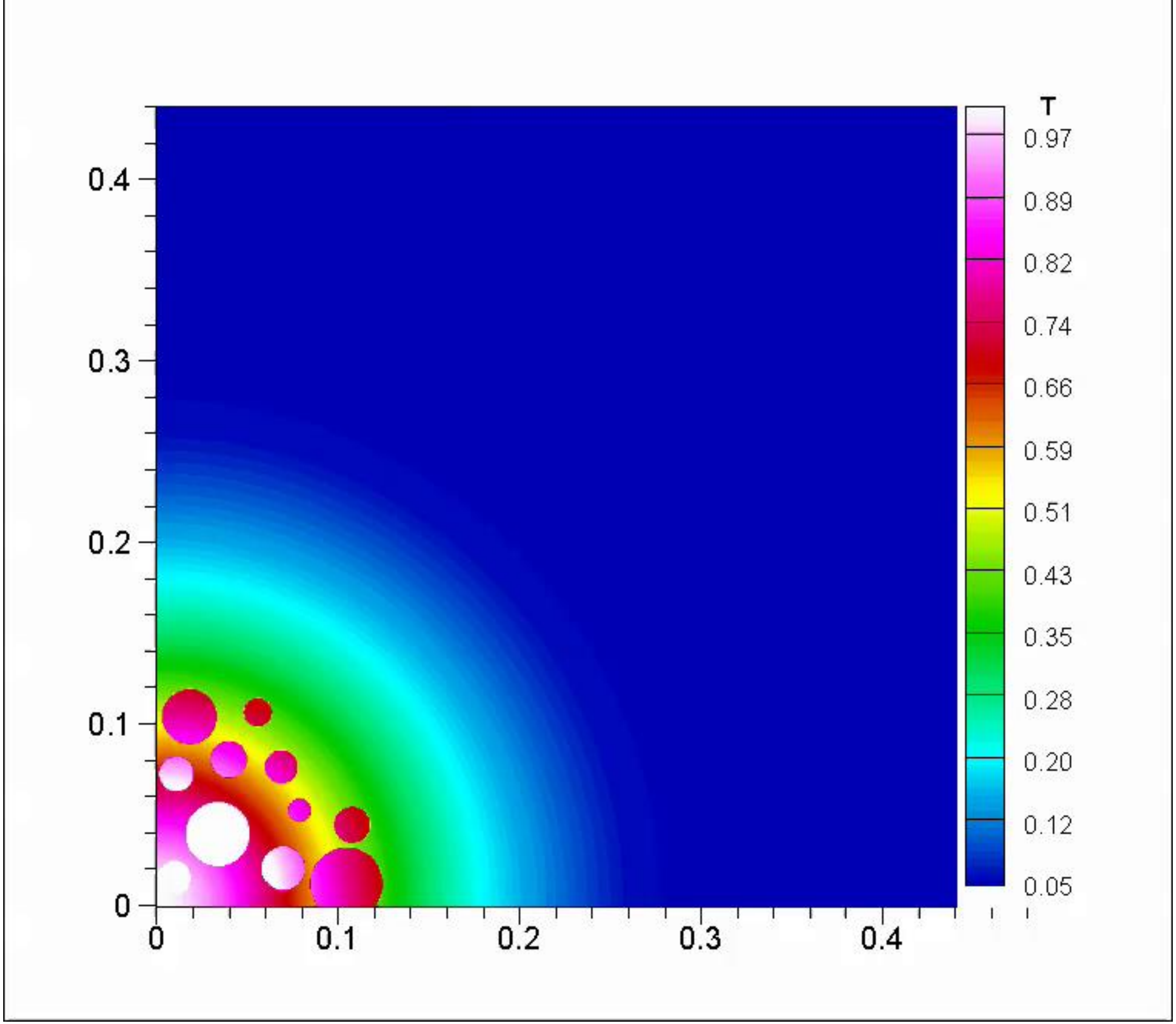
In the central region where the temperature is higher the elements are transformed by further reactions of capturing alpha-particles to the elements of the iron group up to Ni56 (example with 90 solar mass).

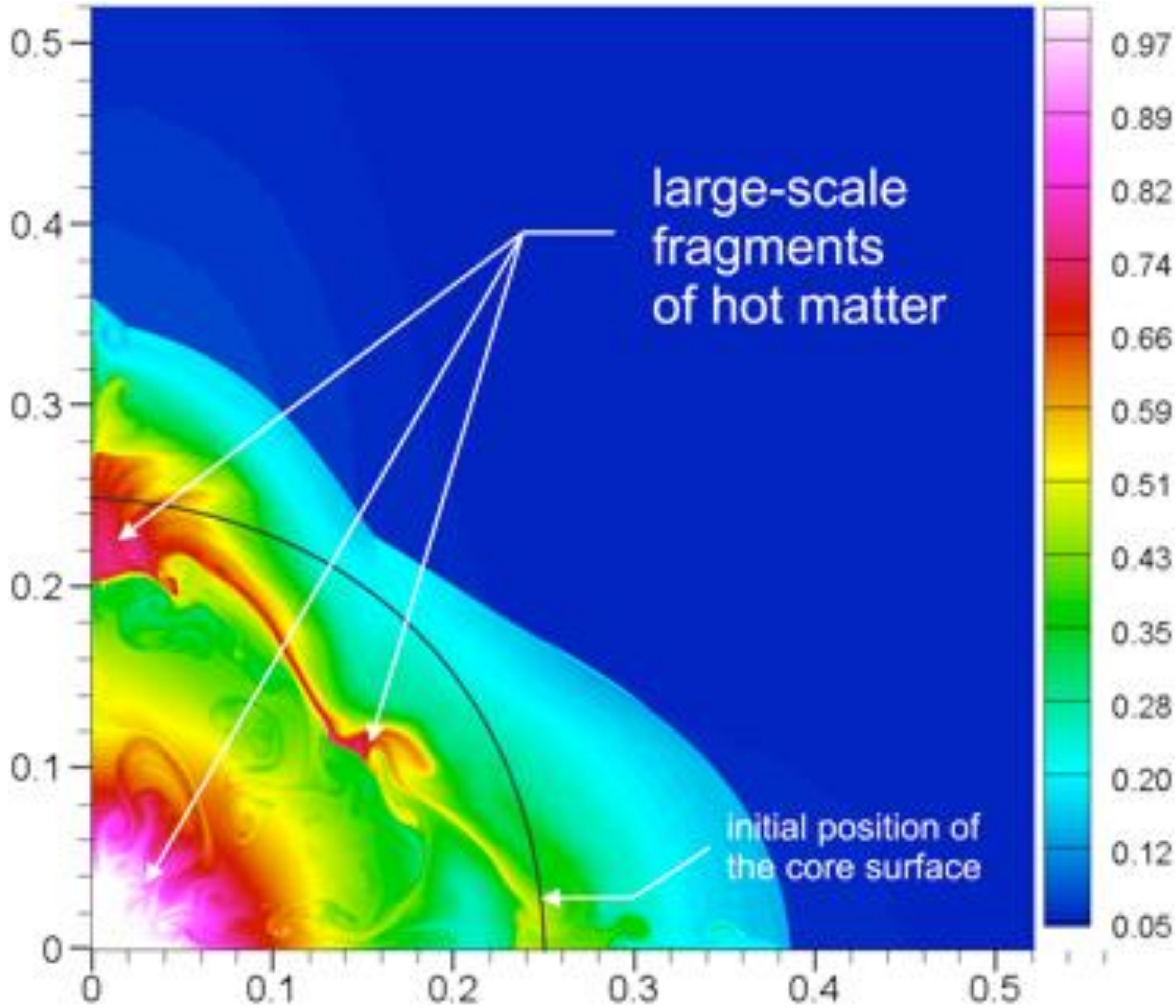

D
-0.17
-0.53
-0.89
-1.25
-1.61
-1.97
-2.33
-2.69
-3.06
-3.42
-3.78
-4.14
-4.50
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7


60 Msol
T
0.97
0.89
0.82
0.74
0.66
0.59
0.51
0.43
0.35
0.28
0.20
0.12
0.05
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7



at t=25 s, in the central part of the core there is a region where a Rayleigh Taylor instability occurs. The radius we found is very similar to the one obtained by Chen with Castro Code


T
0.97
0.89
0.82
0.74
0.66
0.59
0.51
0.43
0.35
0.28
0.20
0.12
0.05
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4

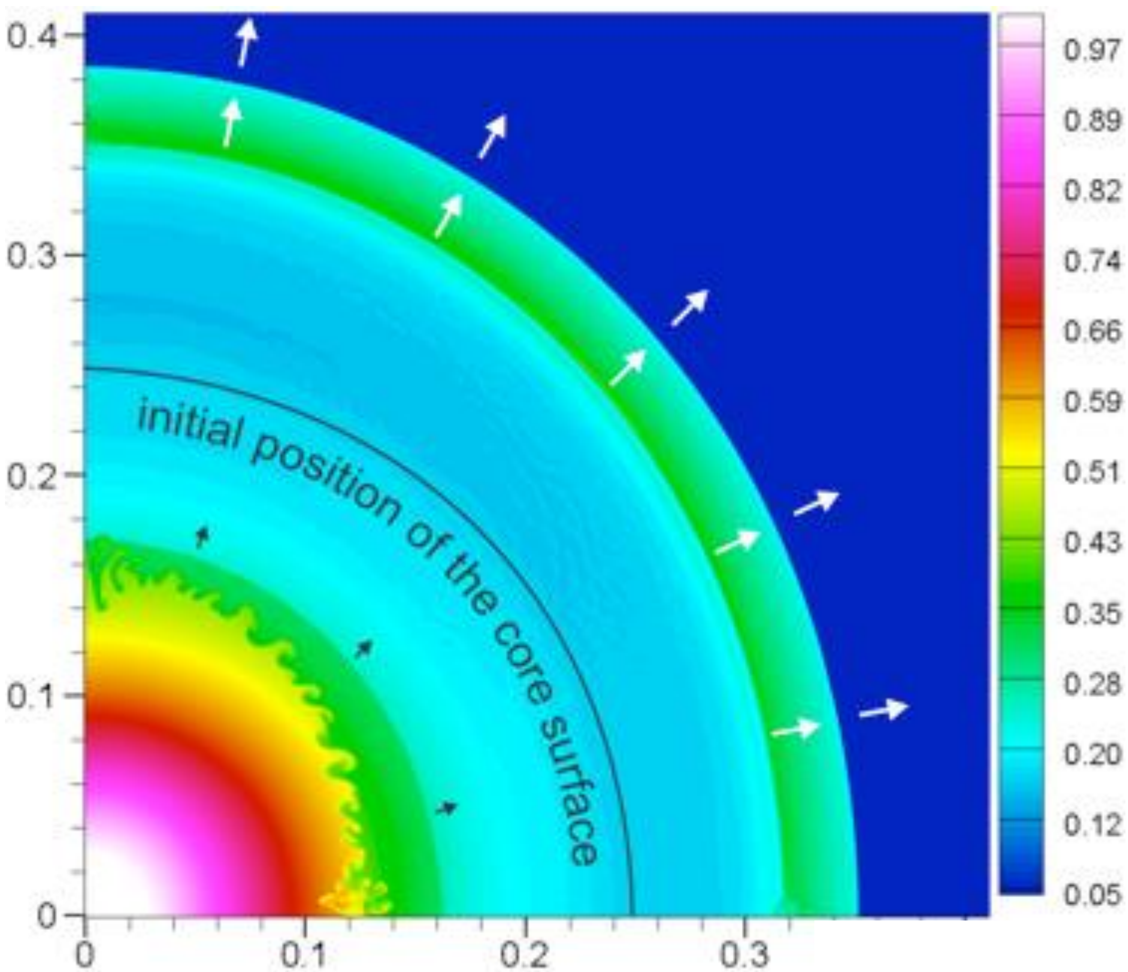

large-scale fragments of hot matter
initial position of the core surface
0.97
0.89
0.82
0.74
0.66
0.59
0.51
0.43
0.35
0.28
0.20
0.12
0.05
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5

Computations in 3D code.

Implement into 3D hydrodynamical code MARPLE a new physical block that will take into account the nuclear energy that is released from nuclear burning inside a star.

Prediction of the elements abundance with tracer particle methods for tracking chemical elementes produced during core explosion in 3D code.

Conclusion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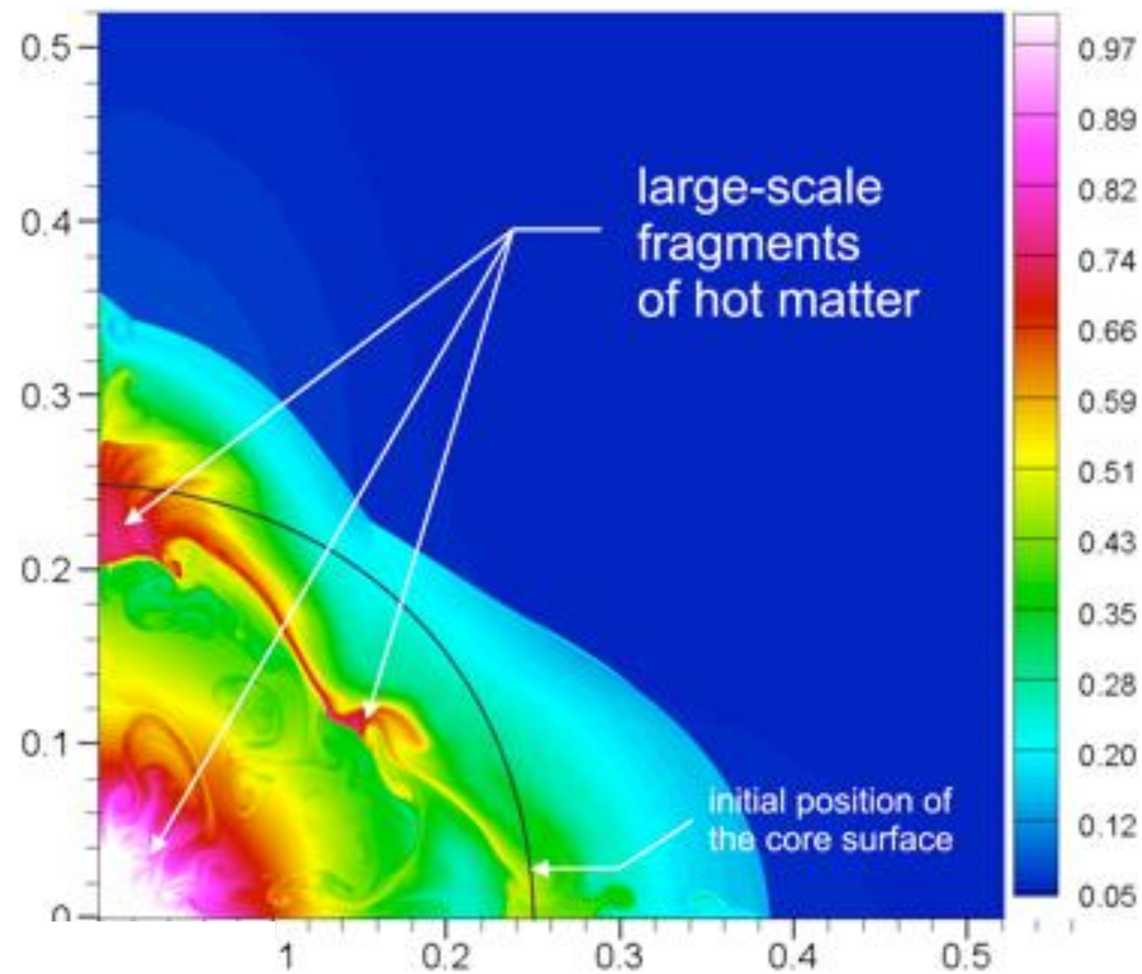
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